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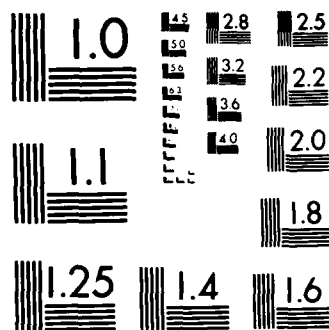
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FINAL TECHNICAL REPORT  
PROJECT A-3273

## DEVELOPMENT OF AN EM-BASED LIFEFORM DETECTOR

By

Joseph Seals  
Steven M. Sharpe  
Anita MacDonald

Prepared for

NAVAL MEDICAL RESEARCH AND DEVELOPMENT COMMAND  
National Naval Medical Center  
Bethesda, Maryland 20014

Prepared by

BIOMEDICAL RESEARCH DIVISION  
Electronics and Computer Systems Laboratory

Under

Research Contract No. N00014-82-C-0390

October 1986

# GEORGIA INSTITUTE OF TECHNOLOGY

A Unit of the University System of Georgia  
Atlanta, Georgia 30332

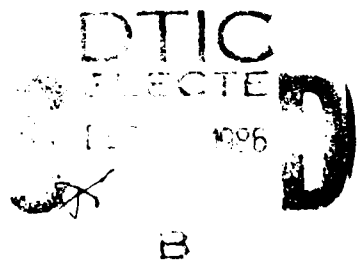


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Georgia Institute of Technology  
Atlanta, Georgia 30332

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## FOREWORD

This final report summarizes research efforts performed on this program from 1 March 1985 to 30 April 1986 by personnel of the Biomedical Research Division in the Electronics and Computer Systems Laboratory of the Georgia Tech Research Institute at Georgia Institute of Technology, Atlanta, Georgia. The program is sponsored by the Naval Medical Research and Development Command contracting through the Office of Naval Research. Within the navy, the program is identified as Contract No. N00014-82-C- 0390, and it is designated by Georgia Tech as Project A-3273. Dr. Elliott Postow of the Naval Research and Development Command is serving as Program Monitor. Mr. Joseph Seals and Dr. Steven M. Sharpe of the Biomedical Research Division are serving as Project Director and Assistant Project Director, respectively. Staff members from the Biomedical Research Division that have contributed to this program include Ms. Anita H. MacDonald, Mr. Bernard M. Jenkins, and Mr. Robert E. Voeks.

Respectfully submitted,

*J.C. Tolw*  
for Joseph Seals,  
Project Director

## I. INTRODUCTION

Under sponsorship of the Naval Medical Research and Development Command, the Georgia Tech Research Institute is developing an EM-based Lifeform Detector (LFD) capable of long-range, remote sensing of the medical status of battlefield casualties. The current research goal is a LFD that is able to query the life status (i.e., alive or dead?) of battlefield casualties from ranges in excess of 100 meters without exposing medical personnel to unnecessary hazards. The LFD employs radiated electromagnetic fields to directly detect the minute body motions associated with respiratory and cardiac activity. Thus, casualties being evaluated are not required to carry transponders or any other type of monitoring device that might fail under battlefield conditions. This feature significantly enhances the potential reliability and versatility of the LFD.

Unique features of the LFD include a millimeter-wave operating frequency (35 GHz) and a coherent frequency modulation approach (FM-CW). The short wavelengths at 35 GHz permit high motion sensitivity and narrow-beamed antennas to be achieved using compactly-sized components. The FM-CW approach enables range discrimination and high receiver performance to be achieved with a system that is sophisticated yet only moderately complex. Several different versions of the LFD have been built and tested during this program. Efforts during the initial three program years were aimed at verifying that the sensitivity required to detect minute body motions from long ranges could be achieved with a practical system. Tests performed under controlled conditions confirmed that the required motion sensitivity could be achieved and based on these results, a goal was established to achieve an operating range of at least 100 meters.

Tests during the third program year indicated the version of the LFD existing at that time was sufficiently sensitive for long range operation. However, this performance had been successfully demonstrated only under controlled conditions. The LFD had not been tested under more typical field conditions because it was suspected clutter (reflections from grass, trees, and other unwanted targets) would be a severe range-limiting problem. In anticipation of the suspected clutter problem, several steps were taken to provide the LFD with an effective clutter-suppression capability. However, due to the uniqueness of the LFD application, there was little available information that was useful in establishing the level of clutter-suppression that would actually be needed. Thus, the clutter-suppression features implemented by the

end of the third year represented a compromise based on the performance limitations of existing system components (the narrow tuning bandwidth of the 35 GHz Gunn oscillator was the most significant limitation) and estimates of the expected clutter levels.

To achieve clutter-suppression, it was judged that it was necessary for the LFD to be able to selectively interrogate small volumes of space that included the casualty being evaluated, but only a minimal number of clutter-producing objects. During the initial three program years, efforts to achieve adequate clutter-suppression included development of high-directivity antennas that produced extremely narrow antenna beams, and a transmitter-receiver approach with ranging capabilities that provided a measurable level of discrimination against clutter based on target range [1]. However, in field tests performed at the beginning of the fourth program year (May 1985), the performance of the LFD was found to be compromised by clutter, indicating that more powerful clutter-suppression capabilities were needed.

Analysis and testing of the LFD following the 1985 field tests revealed several possible reasons for the LFD's inadequate clutter-suppression. These possibilities included (1) the relatively wide (10 meters) range cells produced by the LFD's ranging system, (2) range sidelobes due to the use of a uniform weighting function in processing the demodulated return signals from the LFD, (3) radiation sidelobes or other problems associated with the lens antenna system employed in the LFD, and (4) inadequate signal processing. Information in the next section of this report reviews efforts during the fourth program year to investigate and alleviate these possible problems.

As the remaining sections of this report are reviewed, it will be noted that significant improvements were made to the LFD during the fourth program year. The key improvement was the refinements made to the LFD's ranging system. These refinements included the ability to produce significantly smaller range cells (one-meter wide versus the ten-meter wide range cells used in the 1985 field tests) and the reduction of range sidelobes through use of sophisticated, digitally-generated windowing functions. In field testing of the new ranging system at the end of the fourth program year (March-April 1986), respiratory signals could be detected from ranges extending to 122 meters, a tremendous improvement over the performance of the LFD in the 1985 field tests. However, during periods when the clutter level was very high, the performance of the LFD was not always reliable.

Evaluation of the current LFD indicates that the keys to achieving improved system reliability include further refinement of the ranging system and addition of a signal processing system that exploits differences between the signals (respiratory and cardiac signals) and noise (clutter). The refinements to the ranging system must include verifying that the current system operates in the designed manner. There is concern that various component imperfections are causing the clutter-suppression of the ranging system to be less than expected, especially for clutter from close-in sources. There is also concern that inherent or extraneous phase noise in the 35 GHz oscillator may induce clutter-like effects when return signals are received from stationary objects (e.g., the ground). Once these possible problems are evaluated and the performance of the ranging system has been verified, the necessity and feasibility of further reducing the range-cell size will be determined. If necessary, some reduction in range-cell size should be possible with the new 35 GHz Gunn oscillator currently being employed since its full tuning bandwidth is not being utilized. However, an alternative oscillator may be required if the range-cell size must be made appreciably less than one meter.

In the area of signal processing, efforts during the fourth year indicated that optimum detection of respiratory and cardiac signals can be performed by using a likelihood ratio receiver to process the output of the LFD. One implementation of this type of processor would use estimates of the suspected signal-plus-noise spectrum and noise-only spectrum to compute a likelihood ratio (or series of likelihood ratios) which would be compared to a suitable detection threshold. Initially, the processor would simply make a yes or no decision concerning the life status of the casualty being evaluated. However, as the signal and noise are better characterized through future field tests, it may prove feasible to give the processor added capabilities. For example, in cases where no life was indicated but the clutter was high, the processor could suggest that further processing be performed (to compensate for the low signal-to-noise ratio) before making a final yes-no decision of life status.

## II. SUMMARY OF FOURTH YEAR EFFORTS

Efforts during the fourth year of this program focused on testing and improving the clutter-suppression provided by the LFD. The previously-used ranging system was reevaluated and several refinements, principally narrower range-cells widths and greater suppression of range sidelobes, were incorporated into the LFD. In addition, the radiation patterns of the custom-lens antennas developed for the LFD were carefully measured to determine if these antennas performed as designed. A series of field tests was then conducted near the conclusion of the fourth year to evaluate the performance of the LFD. Results from these field tests were extremely encouraging and aided in identifying additionally needed system improvements. Implementation of a signal processing system that improves and automates the detection performance of the LFD was one clear need. Signal processing investigations during the fourth year directed that a likelihood ratio receiver should be used to achieve optimum detection of respiratory and cardiac signals from the LFD. One version of this type of processor which utilizes spectral estimates of the signal and noise to compute the required likelihood ratio, is currently being implemented. Details of each of these fourth-year efforts are reviewed in the following discussion.

### A. Improved Ranging System

The LFD being developed on this program uses frequency modulation to discerning between return signals from different ranges. In this basic ranging scheme, the frequency of the demodulated return signal from a specific target is proportional to that target's range ("target" refers to any object within the beam from the LFD's antenna). With proper design, the frequency of the demodulated return signal can be made to vary directly with the target range. For example, in one design, the frequency of the demodulated return signal would be centered at a frequency of 25 kHz for a target at a range of 25 meters. Similarly, for a target at a range of 50 meters, the demodulated return signal would be centered at a frequency of 50 kHz. With this approach, range discrimination ideally can be achieved by employing a bandpass filter or tunable receiver that passes information (frequencies) from the desired range while information (frequencies) from undesired ranges is blocked. However, practical constraints (e.g., the need to recycle the modulating ramp) compromise the

performance of this approach and prevent perfect range discrimination from being achieved. These imperfections take the form of range cells of finite width and unwanted range sidelobes.

The ability to discriminate between objects that are close together is determined by the range-cell width. With the frequency modulation approach employed in the LFD, the range-cell width is inversely proportional to the tuning bandwidth of the oscillator used to produce the interrogating electromagnetic field. Until recently, the oscillator used in the LFD had a tuning bandwidth of only 20 MHz. The narrowest range-cell width that could be obtained with this tuning bandwidth was approximately 7 meters (although 10 meters was generally used). Thus, a high degree of range discrimination was not possible.

Other problems also served to limit the range-cell widths that could be achieved with the previous oscillator. At longer ranges, it was often necessary to use 50 percent or less of the oscillator's tuning capacity because of limitations in the LFD's receiver. Thus, the range-cell width could be as large as 15 meters. Additionally, the tuning response of the previous oscillator was found to be nonlinear. Preliminary analysis indicated one effect of this nonlinearity was broadening of the range-cell width from theoretically predicted values.

During the fourth year, a new 35 GHz Gunn oscillator was incorporated into the LFD. This oscillator has a total available tuning bandwidth of over 400 MHz. Range-cell widths less than one-half meter are theoretically feasible with this bandwidth. The tuning response of the new oscillator is also significantly more linear than that of the old oscillator. Thus, the actual range-cell width should more closely approximate predicted values. To insure system reliability, the total tuning capacity of the new oscillator is not being employed. Instead, the tuning bandwidth (or frequency deviation) has been set to a level that produces a range-cell width of approximately one meter. This represents a significant improvement in performance over that obtained with the old Gunn oscillator, yet the range-cell width is sufficient to permit the range of the LFD to be reliably set.

In addition to finite range-cell widths, the effects of range sidelobes are a potentially significant problem. To understand the phenomenon of range sidelobes, it is informative to first examine the basic demodulation approach used in the LFD. A ramp-shaped modulating waveform is applied to the Gunn

oscillator in the LFD. To demodulate the return signal from a target (it is convenient to consider the case where the target is a single point), a homodyne detection scheme is used to mix the return signal with a reference signal from the Gunn oscillator. The return signal will be slightly delayed because of the time required to travel to and from the target and thus, will be offset in frequency from the reference signal.

If the difference-frequency term that results from mixing of the reference and return signals is recovered, the demodulated return signal takes the form of a series of sinusoidal bursts that repeat at a rate equal to the modulating frequency (the burst-like nature of the demodulated return signal results from the periodic recycling of the modulating ramp). Within each sinusoidal burst, the demodulated signal will appear to contain a single frequency which is determined by the specific target range. However, discontinuities will be present at the end points of each sinusoidal burst due to recycling of the modulating ramp. These discontinuities cause the demodulated return signal to have a complex spectrum that prohibits ideal ranging from being achieved with a simple filter or tuned receiver.

Generally, the spectrum of the demodulated return signal contains harmonics of the modulating frequency. These harmonic components produce undesired range sidelobes. The level of the range sidelobes will be lower than that of the main range lobe (at a frequency corresponding to the actual target range). However, effects of the range sidelobes can be quite profound, especially when clutter is strong and/or distributed over a large area, as is the case for clutter sources such as grass or trees. Thus, range sidelobes can allow clutter-related return signals from regions outside the main range cell to mask relatively weak casualty information in the main range cell.

As noted, range sidelobes result from discontinuities that occur at the endpoints of each sinusoidal burst. Classes of weighting functions (also referred to as "windows") exist which can substantially reduce the effects of these discontinuities. To achieve range-sidelobe suppression in this manner, the demodulated return signal is multiplied by a weighting function synchronized with the sinusoidal bursts in the demodulated return signal. Weighting functions are usually bell-shaped and have a value of unity at their center with ends that taper to a small value (a diagram of several common weighting functions is shown in Figure 1 [2]). The resulting product of the demodulated return signal and the selected window still contains discontinuities, but the

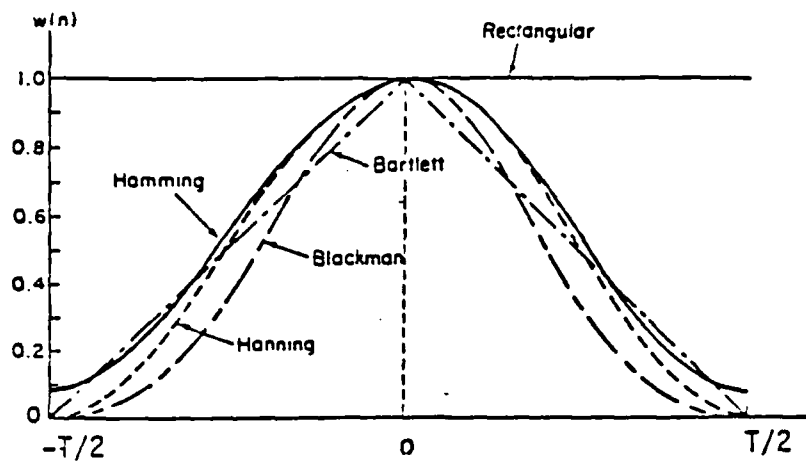


Figure 1. Time domain representation of typical weighting functions used for range sidelobe suppression [2].

Rectangular:  $w(t) = 1$

Bartlett :  $w(t) = 1 - 2\left|\frac{t}{T}\right|$

Hanning :  $w(t) = .5 + .5 \cos\left(\frac{2\pi t}{T}\right)$

Hamming :  $w(t) = .54 + .46 \cos\left(\frac{2\pi t}{T}\right)$

Blackman :  $w(t) = .42 + .5 \cos\left(\frac{2\pi t}{T}\right) + .08 \cos\left(\frac{4\pi t}{T}\right)$

Kaiser :  $w(t) = I_0 \left[ \beta \sqrt{1 - \left(\frac{2t}{T}\right)^2} \right] / I_0(\beta)$

Note: All functions are defined to be zero if  $|t| > \frac{T}{2}$   
where  $T$  is the modulation period.

weighting procedure reduces their significance and results in a more ideal spectrum.

In particular, range sidelobes in the modified spectrum are lowered, and the main lobe, corresponding to the desired range cell, is slightly broadened (the range cell can be returned to its original width by increasing the amount of frequency deviation). Tradeoffs between sidelobe suppression and range-cell broadening vary as a function of the specific weighting function. During the fourth year, computer plots were generated to evaluate the predicted performance of several different weighting functions, including commonly used functions such as the Bartlett, Hanning, and Hamming windows, as well as more sophisticated functions such as Kaiser windows [2]. These plots were obtained by taking the Fourier Transform of individual weighting functions. Results of this comparison, showing the significant range sidelobe suppression that can be achieved, are summarized in Table 1.

Examples of computer-generated plots of the ranging performance predicted for several weighting functions are shown in the graphs comprising Figures 2-6. The ranging performance for the case of uniform weighting is shown in Figure 2. Uniform weighting corresponds to multiplication by unity and represents the "no weighting" ranging performance of earlier versions of the LFD. Examination of Figure 2 shows that the range sidelobes are only slightly lower than the main lobe. Thus, when weighting is not used, clutter from ranges corresponding to the range sidelobe peaks could easily mask the weak signal from a casualty at a range corresponding to the main lobe, even if the clutter and desired target were greatly separated in range. In the rooftop tests performed during Year-2 and Year-3 of this program, clutter from a stand of trees more than 30 meters behind the target often masked desired respiratory and cardiac information. Although the trees were far enough away that they were not contained within the main range cell, their resultant clutter was detected because of range-sidelobes.

The ranging performance obtained with a Bartlett (or triangular) window is shown in Figure 3. Weighting with a Bartlett window corresponds to linear tapering and is relatively simple to implement. When compared to the uniform weighting case, Figure 3 shows that the Bartlett window produces lower range sidelobes (particularly those far removed from the main lobe) and a broader main lobe. Although the simple Bartlett window provides improved performance, significantly better results are possible with more sophisticated weighting

TABLE 1. PERFORMANCE OF SELECTED WEIGHTING FUNCTIONS

Type	3dB Width Relative to Uniform	Peak Sidelobe Level - dB
Uniform	1.000	-13.2
Bartlett	1.433	-26.4
Hamming	1.501	-42.8
Hanning	1.648	-31.7
Kaiser (4)	1.354	-29.9
Kaiser (6)	1.583	-43.8
Kaiser (8)	1.790	-58.7
Kaiser (10)	1.977	-74.1
Kaiser (12)	2.149	-89.9
Kaiser (14)	2.309	-105.9

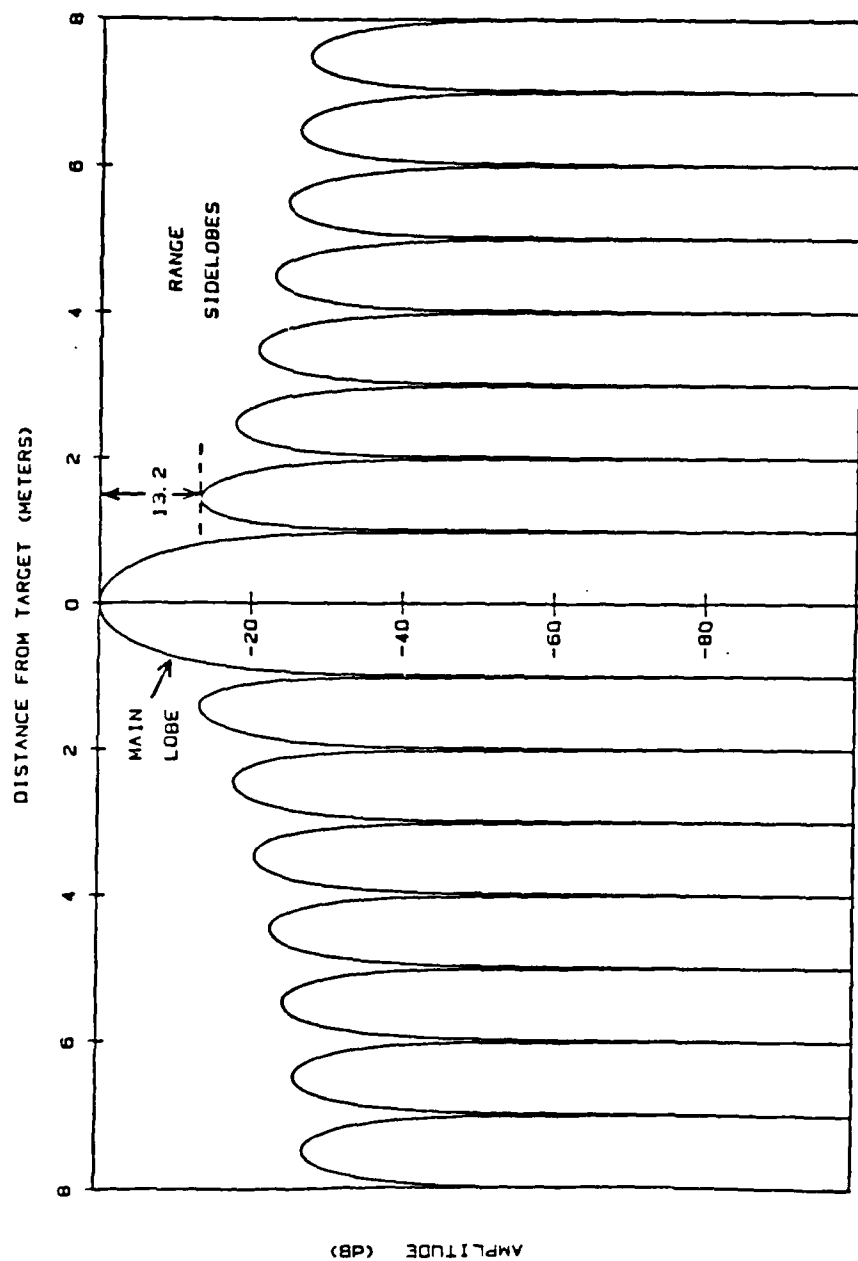


Figure 2. Predicted ranging performance for weighting with a uniform window.

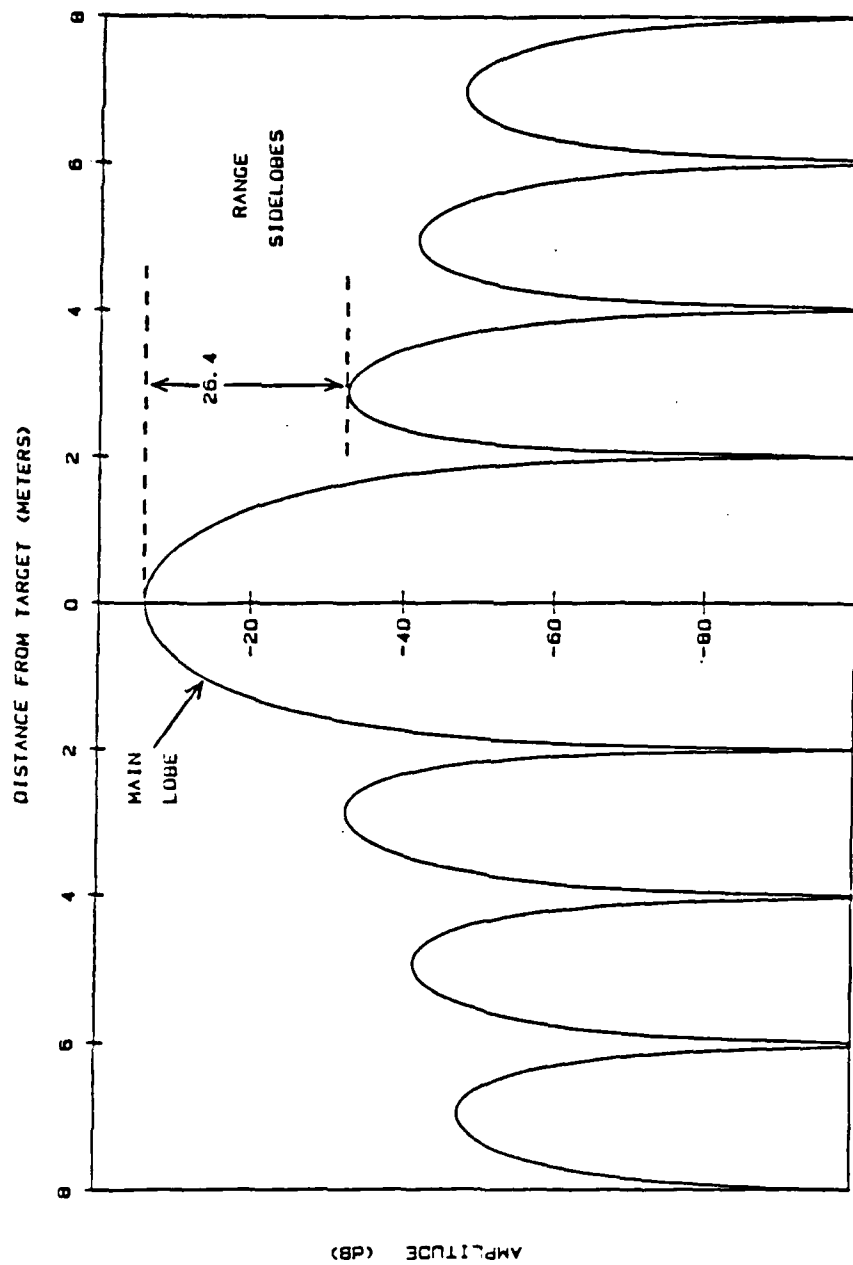


Figure 3. Predicted ranging performance for weighting with a Bartlett (or triangular) window.

functions.

An example of the ranging performance with a Hamming window is shown in Figure 4. This type of weighting provides low nearby sidelobes and a relatively narrow main lobe, but only a modest rate of sidelobe decay. The Hamming window is widely used because it represents a useful compromise between main lobe width and sidelobe performance, and because it is also easy to generate. It is an approximation to one case of the Taylor function [3], widely used in antenna design, which is itself an approximation to the Dolph-Chebyshev function, known to be optimum in the sense of minimum main lobe width for a given sidelobe level [4]. In this latter case, the sidelobe level is constant. That is, there is no sidelobe decay.

Two examples of ranging performance using the Kaiser family of windows [5], which are approximations to the Prolate Spheroidal Wave functions, known to be optimum in the sense of maximizing the energy in the main lobe for a given peak sidelobe amplitude [6], are shown in Figures 5 and 6. The Kaiser window is a sophisticated weighting function, not easily generated by conventional analog means. However, a digital approach developed for the LFD can readily generate this function and allow its many advantages to be realized. Comparison of Figures 5 and 6 indicates that tradeoffs between main lobe width and sidelobe level may be achieved by appropriate choice of the Kaiser parameter. Large values of this parameter result in very high range sidelobe suppression. In practice, the extreme suppression shown in Figure 6 is probably not realizable, due to other system inaccuracies. However, substantial suppression is possible, as shown later in this review.

In order to preserve the excellent theoretical performance possible through weighting, the selected window must first be accurately generated, then multiplied with the demodulated return signal. During the fourth year, both analog and digital techniques for accomplishing these tasks were investigated. For generation of the weighting functions, purely analog techniques lack versatility and are usually limited to the simpler functions (such as Bartlett, Hanning, and Hamming). In contrast, digital techniques are extremely versatile and can be used to precisely generate complex weighting functions including the higher order Kaiser windows.

In the LFD system, the desired windows were generated by a computer and then programmed into a CMOS Programmable-Read-Only-Memory (PROM). In operation, this memory is addressed by a counter and generates a sequence of digital words

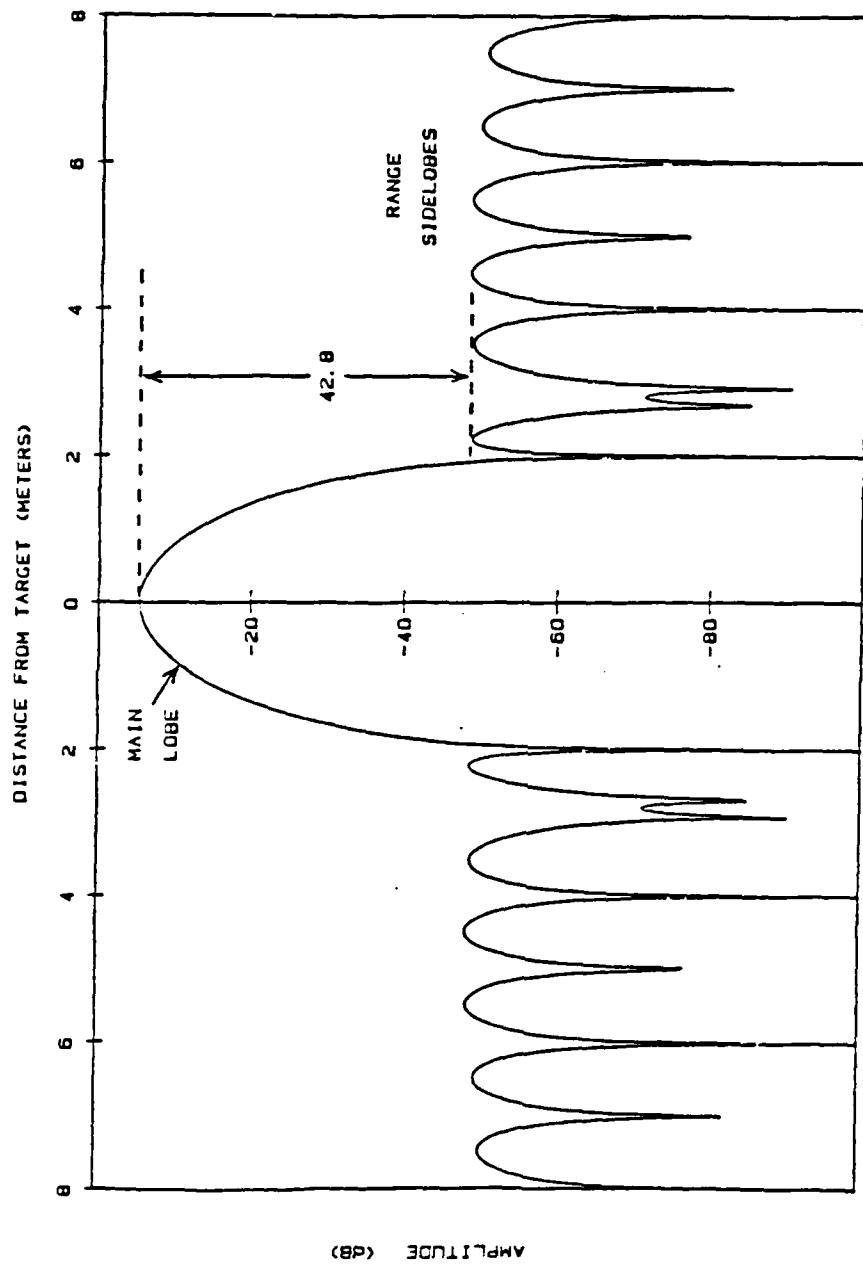


Figure 4. Predicted ranging performance for weighting with a Hamming window.

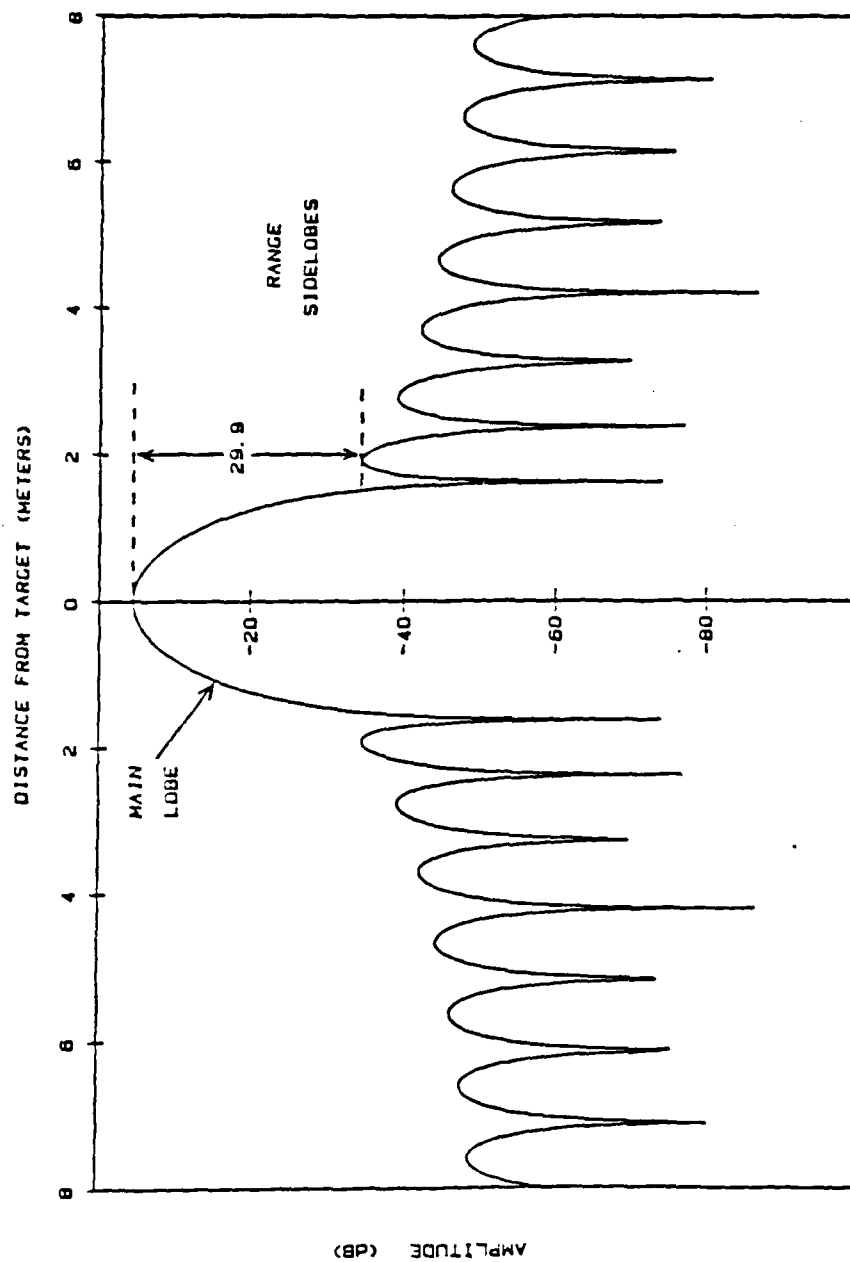


Figure 5. Predicted ranging performance for weighting with a Kaiser (4) window.

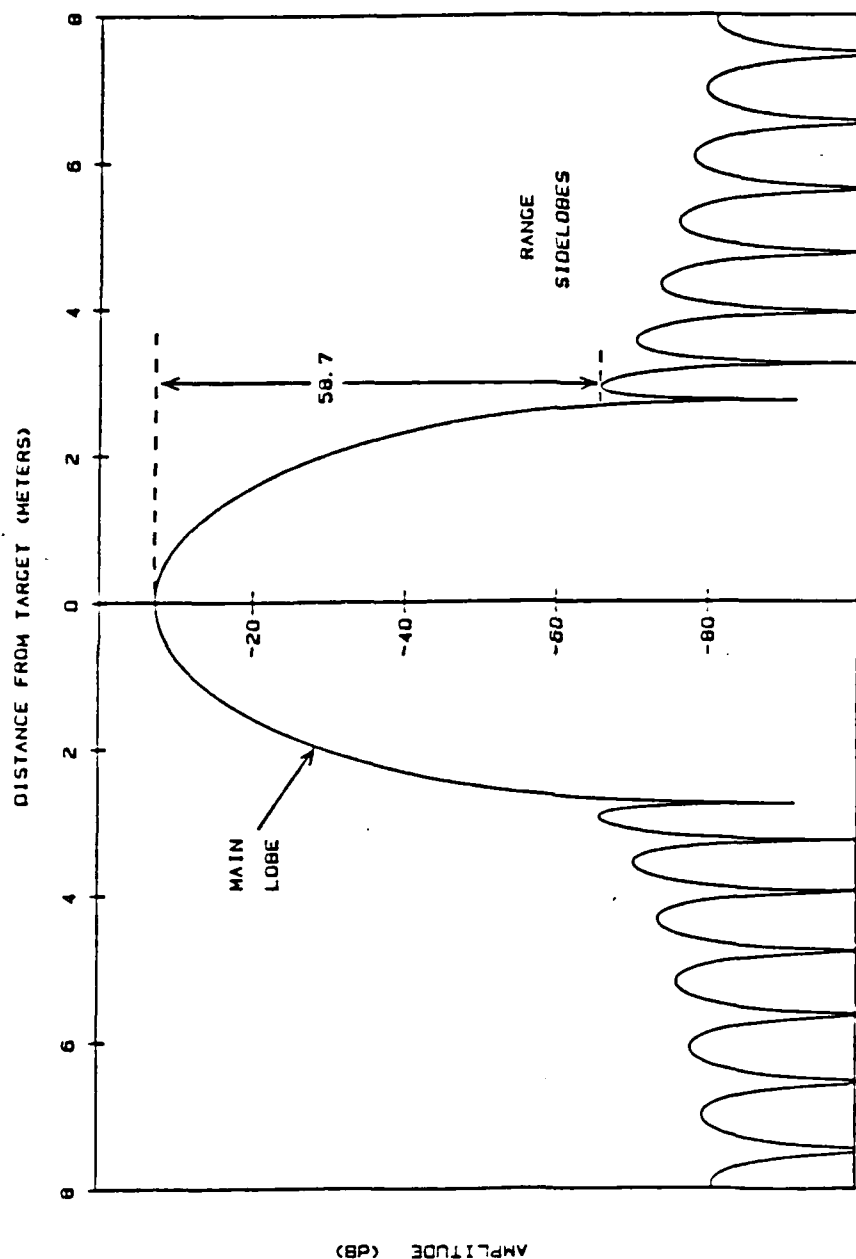


Figure 6. Predicted ranging performance for weighting with a Kaiser window.

corresponding to values of the desired weighting function. These words are then converted to an analog signal by a high-precision, digital-to-analog converter (DAC).

Initially, an 8-bit PROM and DAC were employed to generate the desired weighting functions. However, the limited resolution of this system resulted in quantization errors that compromised the accuracy of the weighting functions that were generated. Therefore, a switch was made to a 12-bit system that is currently being employed. The entire system is reliable, compact, and low in power consumption. In addition, the PROM has sufficient memory capacity to store several weighting functions. This latter capability greatly facilitates testing and evaluation since the performance of different weighting functions can be compared by simply changing a switch setting.

As noted, digital techniques were found to be ideally suited for generating the required weighting functions. However, when digital techniques were used to multiply the weighting function with the demodulated return signals, it was discovered that receiver sensitivity was compromised by digital noise. To minimize this noise problem, a hybrid technique was adopted in which the required weighting function was precisely generated using digital techniques, while low-noise analog techniques were used to achieve the required signal multiplication. A block diagram of the LFD system is shown in Figure 7.

Preliminary tests with this hybrid system were extremely encouraging. In one experiment, the LFD was aimed at a corner reflector at a range of approximately 20 meters. Ideally, the spectrum of the demodulated return signal in this case would contain components only near 20 kHz. However, when uniform weighting was used, strong components were observed across the entire spectrum as shown in Figure 8a. It is suspected the extraneous spectral components observed in this case were due to range sidelobes (see Figure 2 for the ranging function when uniform weighting is used) associated with the corner reflector, the ground, and internal system reflections.

A Kaiser (8) window was then applied to the demodulated return signal. When the resulting spectrum was examined, spectral components due to the corner reflector were present at approximately 20 kHz, as expected. In addition, a large percentage of the previously observed range sidelobes were at least 40 dB lower than had been observed when no weighting was employed (see Figure 8b). This represents a dramatic improvement in the clutter-suppression capabilities of the LFD. Further testing of the ranging system has been performed under

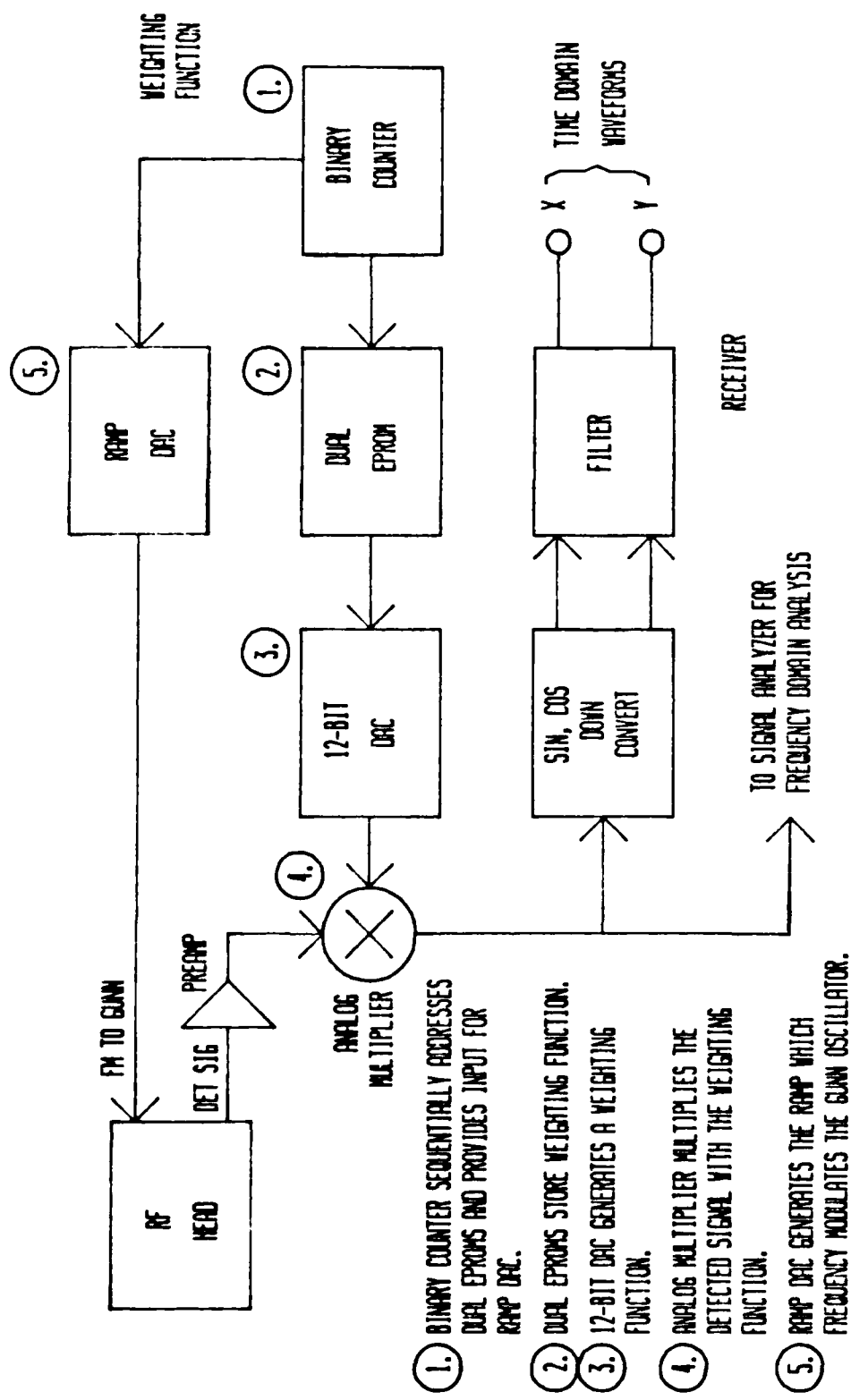


Figure 7. Block diagram of LFD system.

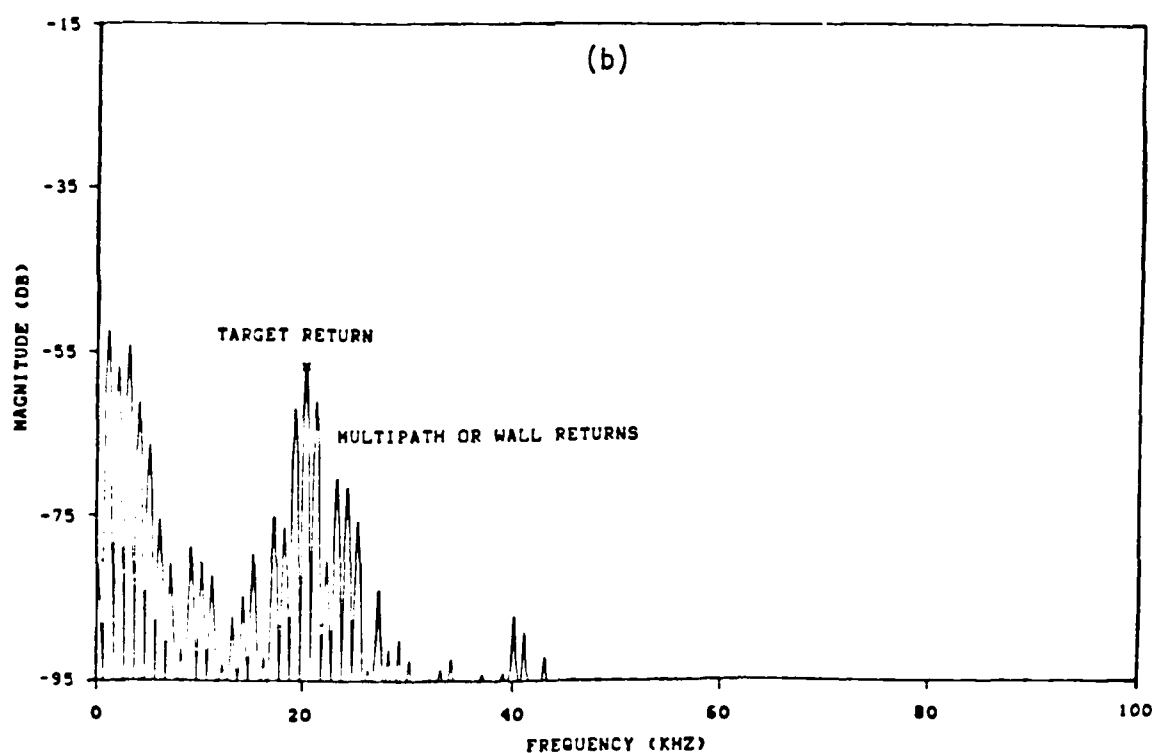
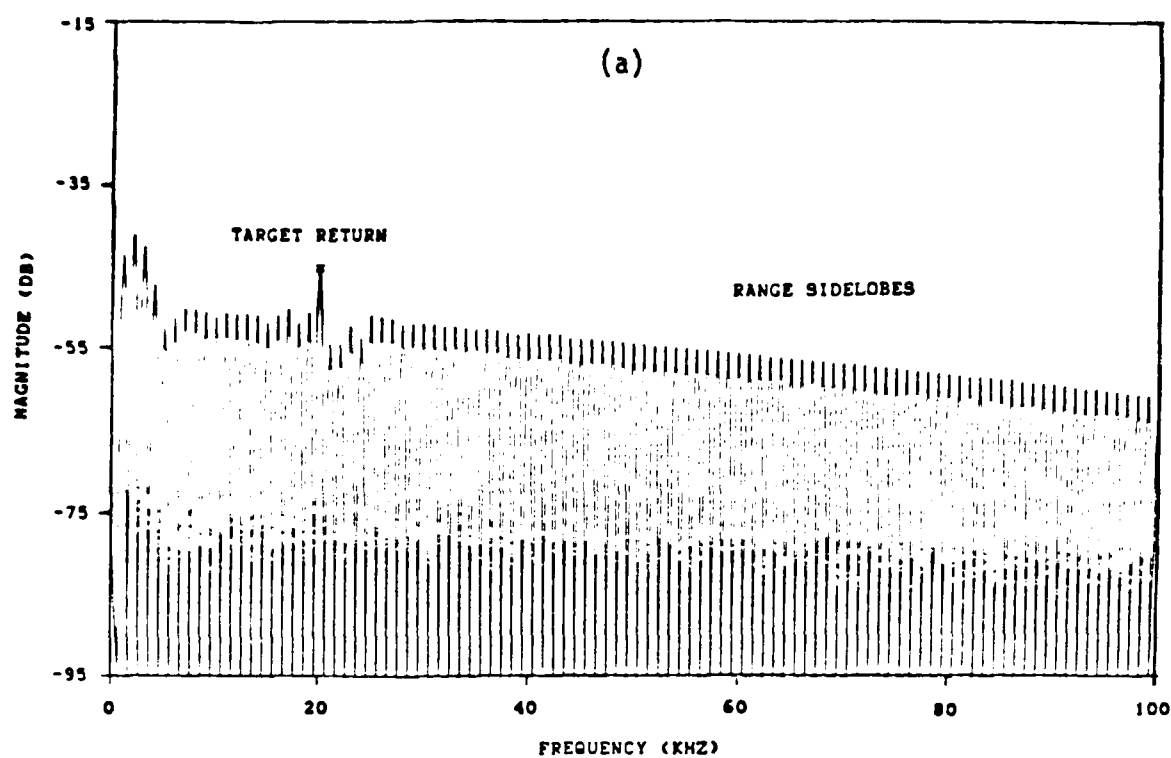


Figure 8. Spectrum of demodulated return signal with LFD aimed at metal corner reflector at a range of 20 meters: (a) weighting with a uniform window, (b) weighting with a Kaiser (8) window resulting in greatly suppressed range sidelobes.

actual field conditions. Results from these tests are discussed in the "Year-4 Field Tests" section of this report.

To facilitate addition of the weighting function to the LFD's ranging system, it was necessary to make some major modifications to the receiver design. To achieve ranging, some characteristic of either the transmitter or receiver must be adjusted to obtain the desired range selectivity. In previous systems, the transmitter's frequency deviation and modulating frequency were adjusted so the demodulated return signal from the desired target range would be at a specific frequency. By adjusting the transmitter in this manner, it was possible to use a conveniently implemented fixed-frequency receiver.

Although this approach was convenient, it was not well suited for implementing the weighting functions needed to achieve better range-sidelobe suppression. Instead, an approach using a fixed transmitter but tunable receiver was preferred. During the fourth year, a new transmitter-receiver design was designed and a large part of the new system was implemented. This design includes a more reliable and efficient detector as well as provisions for eventual incorporation of a system for phaselocking the 35 GHz oscillator.

Although not yet completed, this new approach offers some promising features that should serve to expand the future capabilities of the LFD. One of the most significant of these features is the ability to extract information from any specific target range from the demodulated return signal. This capability could eliminate the need to accurately set the range of the LFD since all range cells in the vicinity of the target could be evaluated. In addition, information from range cells not containing a casualty could provide baseline information useful to the signal processing system for setting the threshold level required to make accurate detection decisions (this idea is discussed further in the Signal Processing Investigations section of this report).

#### B. Testing of Lens Antennas

To determine if clutter observed during preliminary field tests with the LFD was due to imperfections in the LFD's horn-fed lens antenna, an extensive series of antenna pattern measurements was performed in August and September (1985) on both the six-inch and nine-inch lens systems. Pattern measurements previously performed on an early version of the six-inch lens antenna indicated the lens approach produced both a narrow main beam and low radiation sidelobes.

However, these measurements had been performed on a short, indoor range where accurate measurements on high-directivity antennas are difficult. Therefore, the present lens antennas were retested on an outdoor range where separation distances between the transmitting and receiving antennas could be made as large as 15 meters. Measurements were made for both horizontal and vertical polarizations. In addition, effects of feedhorn position on antenna gain and radiation-sidelobe levels were evaluated.

Because of the symmetrical illumination pattern provided by the custom-built scalar feedhorn, the beamwidth of both lens antennas was found to be symmetrical with respect to polarization. With proper positioning of the feedhorn with respect to the lens, it was found that the antenna gain could be set to within 0.5 dB of optimum while maintaining radiation sidelobes to levels 30-40 dB below the main beam. Examples of the patterns measured for the lens antennas are shown in Figures 9a-9d. This performance appears to be better than the listed specifications of similar commercially available antennas.

The most significant radiation sidelobes were found to occur between angles of approximately  $\pm 45$  degrees (with respect to the main beam, where the main beam is at zero degrees), especially for the vertical polarization of the six-inch antenna. Radiation sidelobes at these angles could cause strong reflections from the ground directly in front of the LFD. If this area is covered with grass or other sources of clutter, the combination of large reflection and short range could produce a signal capable of masking weak casualty information from longer ranges. It is doubtful this potential problem could be significantly improved through modification of the antenna design (although this possibility will be investigated). A more likely prospect is that it will be necessary to depend on the LFD's ranging system to help reduce the effects of any short-range clutter resulting from radiation sidelobes in the patterns of the lens antennas.

The measured 3-dB beamwidths of the six-inch and nine-inch lens antennas are 3.5 and 2 degrees, respectively. Although these beamwidths are extremely narrow, the angle of incidence at which the lens antennas are employed causes the electromagnetic beam radiated by the antennas to intercept a large portion of the ground in front of and behind the target being evaluated. Thus, despite their narrow beamwidths, the lens antennas may not provide as much discrimination against ground clutter as might be expected from simple consideration of the beam spread based on the antenna 3-dB beamwidths and target

range.

This problem could be minimized by using more directive antennas. However, this could require substantially increasing the size of the present antennas (undesirable in view of the required system portability) and could make accurate aiming of the LFD difficult. Thus, alternate solutions are desirable. Fortunately, problems due to the antenna beamwidth will benefit from the improved ranging system, provided the main range cells are made sufficiently narrow, and the range-sidelobe levels are sufficiently suppressed. That is, ranging can effectively improve the target selectivity of the lens antenna without requiring any inconvenient increases in antenna size.

To achieve these benefits it is imperative that the ranging system operate in the designed manner. Because the measured radiation sidelobe degrees may produce strong reflections from the ground immediately in front of the LFD, the ranging system must be particularly effective at suppressing clutter from close-in sources. Measurements are currently in progress to determine if the close-in clutter suppression provided by the various weighting functions that have been implemented is sufficient to overcome imperfections (radiation sidelobes) in the LFD's antennas.

#### C. Year-4 Field Tests

During the past three years, several versions of the LFD have been implemented and evaluated. Each new version of the LFD has incorporated at least one significant improvement over its predecessor. By the conclusion of the third program year, the LFD included features such as a narrow-beam antenna (Year-1), a low-noise homodyne receiver (Year-1 and Year-2), and range-gating (Year-2 and Year-3). Under indoor or rooftop conditions, where troublesome clutter sources could be minimized, this version of the LFD was used to successfully detect respiratory and cardiac motions from ranges extending to 50 meters. Although longer ranges were not tested due to the space limitations of the rooftop test site, the high signal-to-noise ratio (SNR) generally observed under low-clutter conditions indicated that greater detection ranges were feasible, provided clutter could be kept adequately low.

At the beginning of the fourth program year (May 1985), the first extensive effort was made to evaluate the performance of the LFD in a clutter-contaminated environment. The field test was conducted at an isolated, off-campus facility

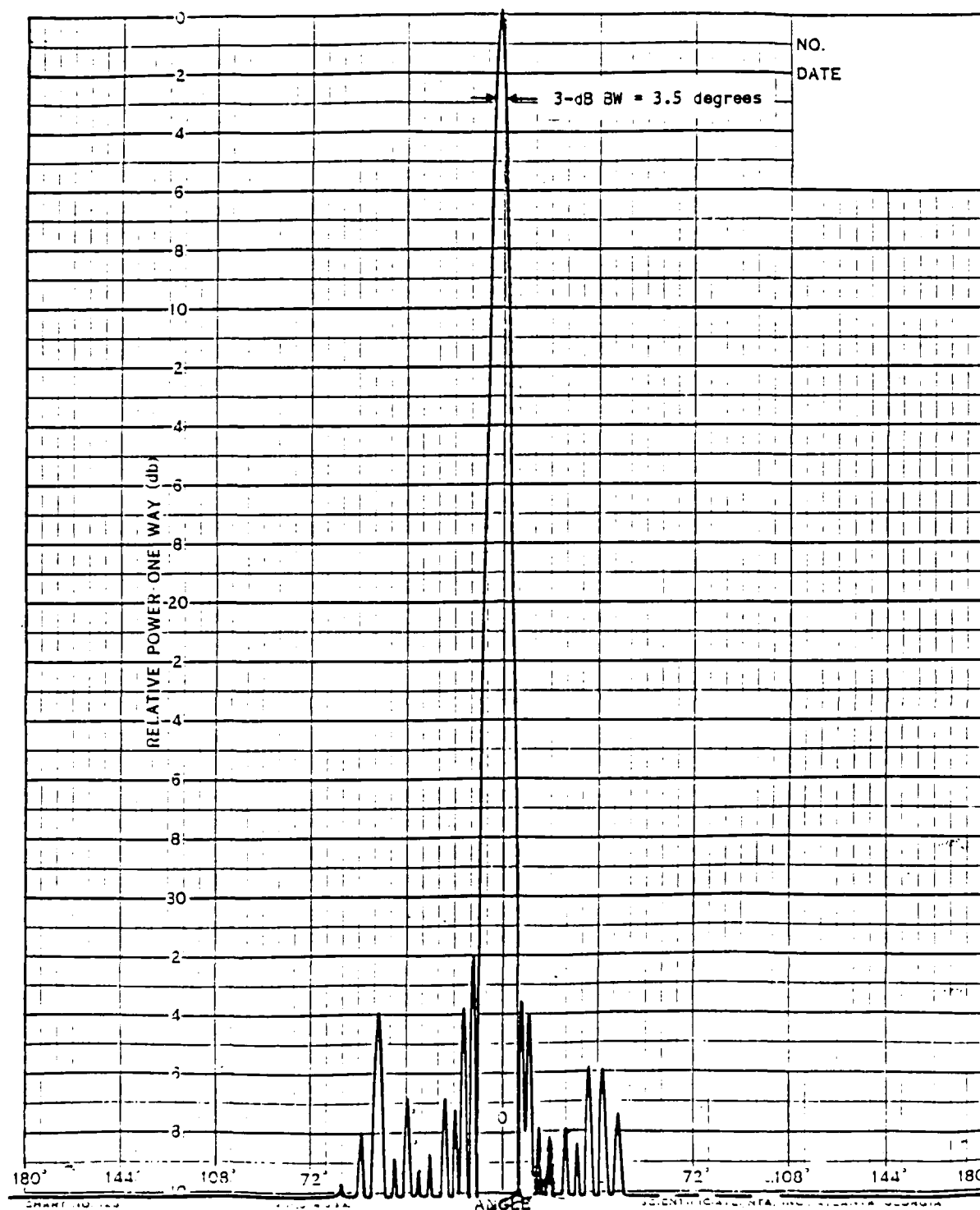


Figure 9a. Antenna pattern for 6 inch lens, vertical polarization.

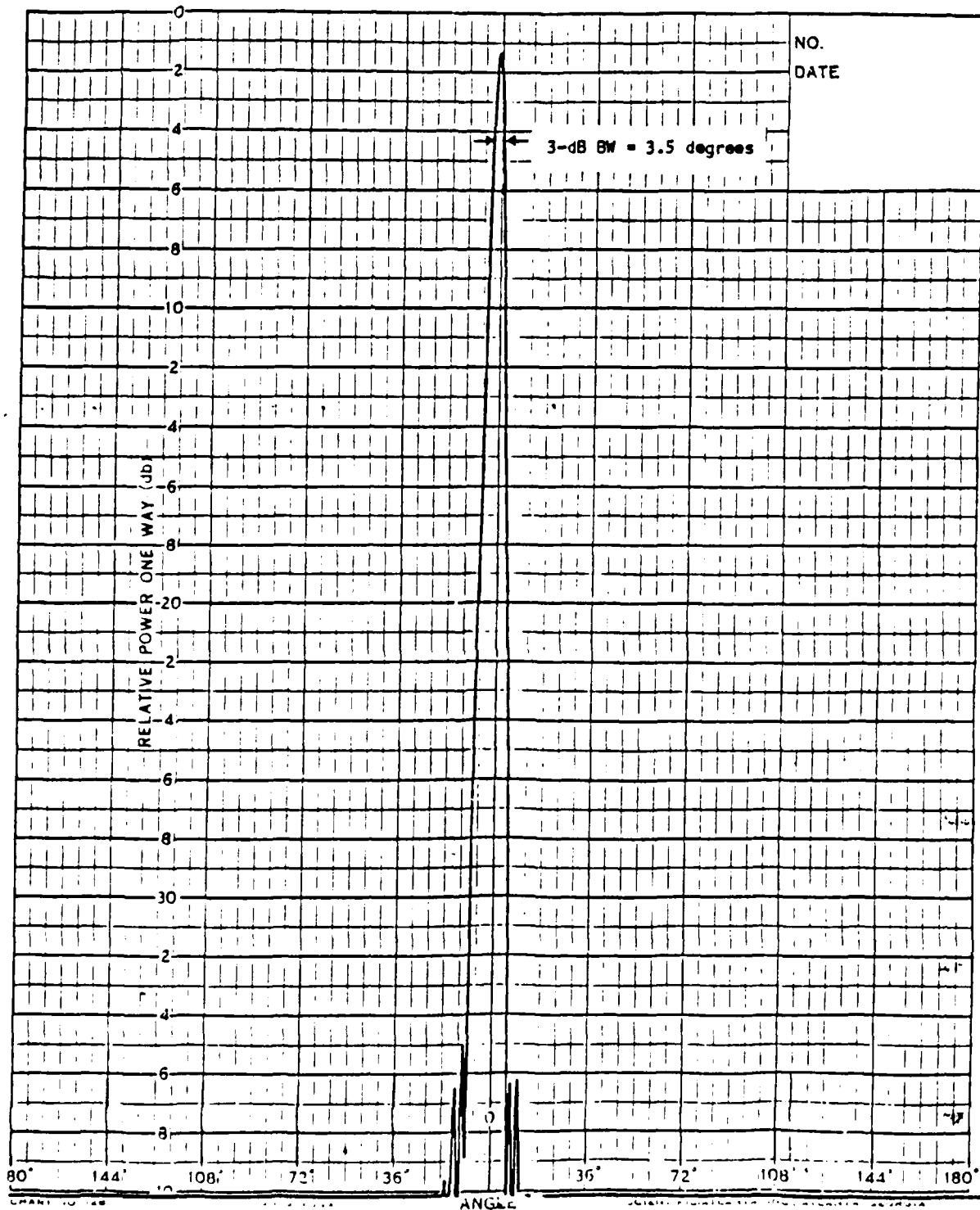


Figure 9b. Antenna pattern for 6 inch lens, horizontal polarization.

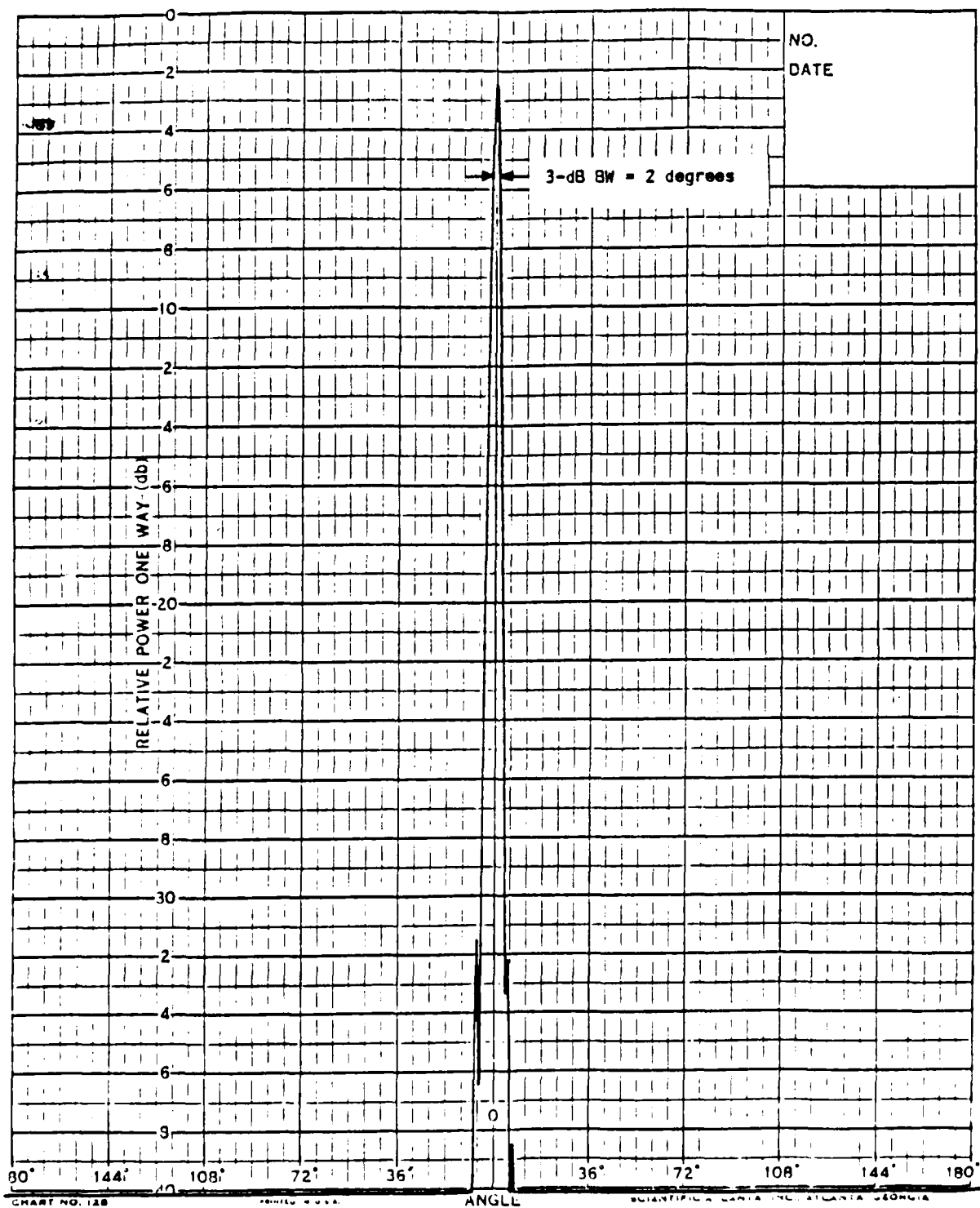


Figure 9c. Antenna pattern for 9 inch lens, vertical polarization.



owned by Georgia Tech and was witnessed by Naval personnel. The field site includes several open areas where ranges of several hundred meters can be attained. An abundance of clutter sources are present at the field site including grass, weeds, and trees, and both flat and hilly terrains.

For this initial field test, the six-inch (diameter) lens antenna, which has a 3-dB antenna beamwidth of approximately 3.5 degrees, was employed. At a range of 30 meters, the beamwidth of this antenna resulted in a beamspread of only 2 meters. However, the antenna was positioned only 1.2 meters above the ground, requiring a low incidence angle to interrogate ground-level targets. The low incidence angle caused a large portion of the ground before and after the target to be grazed by the antenna beam. Therefore, the narrow antenna beamwidth was not effective in reducing clutter from sources in-line with the antenna beam.

To combat in-line clutter, the LFD employed in the 1985 field tests used an early version of a range-gating system based on the previously discussed FM-CW approach. This range-gating system employed uniform weighting and permitted minimum range-cell widths of 7 meters to be achieved (although 10 meters was typically employed). At a target range of 30 meters, a 10 meter range-cell width and a 3.5-degree antenna beamwidth result in an area of ground approximately 18 square meters in size being interrogated by the LFD. A typically-sized adult would occupy an approximate area of only 0.5 square meters. That is, even with a narrow antenna beam and a relatively sophisticated range-gating system, a human target would comprise only a small percentage of the total area interrogated by the LFD from a range of 30 meters.

Not surprisingly, results of the 1985 field tests revealed that clutter believed to be due to grass and weeds in the area of ground interrogated by the LFD completely masked any signals due to respiratory and cardiac motions. It is doubtful that any practical signal processing would have had a significant impact because of (1) the severity of the clutter, (2) the spectral overlap between the clutter and the respiratory and cardiac signals of interest, and (3) the limited amount of signal processing time (30-60 seconds) permissible in this application. Thus, it was apparent that the clutter-suppression capabilities of the LFD would have to be improved if high SNR and long detection ranges, which were observed under low-clutter conditions, were to be obtained in the field.

Following the initial field tests, it was determined that the most practical method for reducing clutter to an acceptable level was improved range-

gating. It was difficult to estimate the amount of improvement (in the form of narrower range cells) that would be needed since the clutter observed at the field site varied significantly with the season (amount and type of vegetation), weather (wet or dry), terrain, and wind conditions. For example, on a given day, it was not unusual for the clutter from the LFD to vary by 20 decibels, or a factor of 10 in voltage, over a period of one minute.

It also was not apparent whether the observed clutter was due to uniformly distributed scatterers. For uniformly distributed clutter sources, observed clutter levels are proportional to range-cell size and can be made arbitrarily small by reducing of the range-cell size. Additionally, by comparing known respiratory and cardiac signal levels (from tests performed under clutter-free conditions) to the worst-case clutter levels observed using the 10-meter range cells, it would be possible to estimate the level of clutter suppression (or equivalently, range-cell reduction) needed to permit respiratory and cardiac signals to be reliably detected under field conditions. For example, if it was determined that the level of the worst-case clutter needed to be reduced by 10 decibels to permit reliable detection, it would be necessary to reduce the range-cell size by a factor of ten.

A uniformly-distributed clutter model appears reasonable for large range-cell sizes. In this case, variations in the clutter distribution are effectively averaged and the clutter level can be estimated by multiplying an average clutter density by a given area. As range-cell size is reduced, the greater range selectivity permits reflections from individual clutter sources to be detected and the usefulness of an average clutter density becomes questionable. Once the clutter can no longer be considered uniformly distributed, it becomes difficult to predict the impact that reduction of the range-cell size will have on the observed clutter level. If the clutter is primarily due to foliage in the immediate vicinity of the target, it could prove necessary to reduce both the antenna beamwidth and range-cell size so that clutter sources are completely eliminated from the area interrogated by the LFD. That is, the only object within the area interrogated by the LFD would be the casualty being evaluated. The practicality of achieving such performance in a portable system, given the scheduling and economic constraints of this program, is an unanswered question at this time.

As described in the preceding part of this report, a decision was made to reduce the range-cell size to one meter during the fourth program year. A one-

meter range-cell size would significantly reduce the area of ground interrogated by the LFD. For example, from a range of 30 meters, only 2 square meters of ground would be interrogated as compared to the 18 square meters that were interrogated when 10-meter range cells were employed. During March and April of 1986, additional field tests were performed to evaluate the adequacy of the improvements made to the LFD's range-gating system during the fourth program year. Major goals during this evaluation included determining (1) the levels of the respiratory and cardiac signals detected by the LFD as a function of range, (2) the adequacy of the receiver in the LFD based on receiver noise measurements and estimated levels for the respiratory and cardiac signals, and (3) the effect of range-cell size on the clutter levels observed with the LFD. Results from the evaluation were then used to determine additional improvements needed in the LFD's capabilities.

The majority of the new field tests were performed on three different test subjects from a range of 61 meters (200 feet). Since no significant signal processing was possible at the field site, only detection of respiratory signals was attempted. In general, respiration could reliably be detected for all three subjects from the 61 meter range. However, significant variations were found to occur in the levels of both the respiratory signals and clutter, and at times, detection of a respiratory signal was not possible using the unprocessed data from the LFD output. This latter result indicates that improved clutter-suppression and/or signal processing will be required to improve the overall reliability of the LFD.

A limited number of the field tests also were performed from ranges of 91 meters (300 feet) and 122 meters (400 feet) for a single test subject. As expected, the levels of respiratory signals from these longer ranges were weaker than those observed from 61 meters. However, clutter was also appreciably lower, with the overall result being that a very clear respiratory signal was observed from both of the longer ranges. Examples of results obtained from 91 and 122 meters, as well as from other ranges tested, are presented in the following field test summaries.

#### 6 March 1986 (30 meters)

In this initial field test with the improved LFD, a target range of 30 meters was used. Because of limitations in the fixed-frequency receiver implemented during the fourth program year, it was necessary to use a range-cell

width of 1.9 meters instead of the designed minimum width of one meter. A very strong respiratory signal was detected with the improved LFD from the 30-meter range. By comparison, respiration could not be detected from ranges as close as 15 meters during the 1985 tests.

The strength of the respiratory signal was approximately 300 millivolts (peak-to-peak voltage levels are used throughout this discussion), while the observed clutter signal was only 100 millivolts. Thus, the respiratory signal may be clearly observed as shown in Figure 10.

From past experience, the cardiac signal is typically 20 decibels lower than the respiratory signal, which would have made the cardiac signal level approximately 30 millivolts. Since this level was below the observed clutter signal of 100 millivolts, detection of a cardiac signal would not have been very practical.

#### 12 March 1986 (30 and 61 meters)

On this date, the LFD was tested from ranges of 30 and 61 meters. For the 30-meter tests, a 1.9 meter range-cell was again used and respiratory signals were successfully detected for the three subjects tested. Generally, respiratory signals varied from 200-400 millivolts while clutter varied from 100-125 millivolts. Both levels were similar to those observed from 30 meters on March 6. However, there were occasions when the levels of the respiratory signal and/or the clutter varied significantly.

For tests from 61 meters, receiver requirements made it necessary to use a range-cell width of 3.7 meters. From this range, a respiratory signal of 40 millivolts was detected. The clutter level was approximately 10 millivolts.

#### 27 March 1986 (30 and 61 meters)

Tests were initially performed from a range of 30 meters using a range-cell width of 1.9 meters. Respiratory signals, varying between 200 and 900 millivolts, were successfully detected from the three subjects tested. Thus, levels of some detected respiratory signals were significantly greater than those observed from 30 meters on March 6 and March 12. Further investigations indicated that variations observed in the respiratory signal levels were associated with body orientation and/or position. Although no conclusions were made with regards to the cause of or possible solutions to the observed variations, it appeared that variations as large as 10-20 decibels could occur.

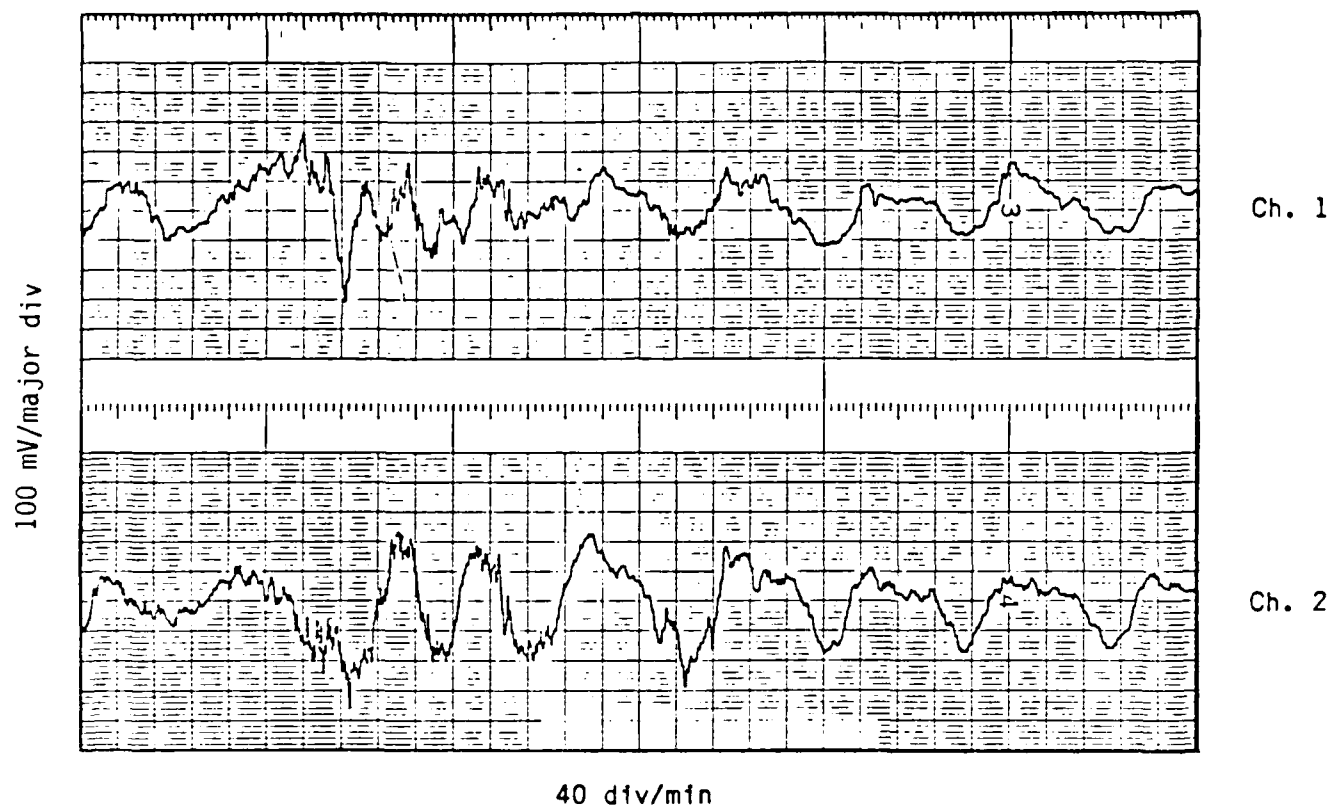


Figure 10. Respiration, 300 mV p-p, detected from 30 meters on 3/6/86.

Clutter measurements were also made at the 30 meter range. The measurements revealed both larger clutter signal levels and larger fluctuations of the clutter signal than had previously been observed. An example, showing the clutter fluctuating between 100 and 1000 millivolts over a period of one minute, is shown in Figure 11.

For tests from 61 meters, a range-cell width of 3.7 meters was again employed. Respiratory signals of 50 millivolts were detected for two of the subjects tested as shown in Figures 12 and 13. The clutter level of 10-25 millivolts observed during testing of these two subjects permitted the 50-millivolt respiratory signals to be easily detected. For the third subject, the clutter level increased to approximately 50 millivolts. This higher clutter level apparently masked any useful information that might have been present in the output of the LFD. The increased clutter levels observed during testing of the third subject were clearly associated with changes in wind conditions. However, the exact mechanism for the increase in clutter was not apparent (e.g., the wind could have affected the foliage, the test subject, or the LFD).

#### 1 April 1986 (61 meters)

Tests were performed from a range of 61 meters using a range-cell width of 3.7 meters. Respiratory signals were detected for each of the three subjects tested on this date. The detected respiratory signals were typically 50-100 millivolts, which was slightly higher than had been observed from this range during previous tests.

Additional measurements were made to better estimate clutter levels at 61 meters. With the test subject removed, the clutter signal was consistently found to be between 30-60 millivolts, which was stronger than had previously been observed from this range. The increase in clutter appeared to be at least partially attributable to the increase in foliage at the field site since the start of this series of tests.

#### 4 April 1986 (61, 91, and 122 meters)

Tests were initially performed from 61 meters using a range-cell width of 3.7 meters. In previous tests, the antenna had been aimed directly at the torso of the test subject lying on the ground (supine). For tests performed on this date, the antenna was aimed approximately one meter above the subject. With this modified aim, it appeared possible to reduce the impact of clutter

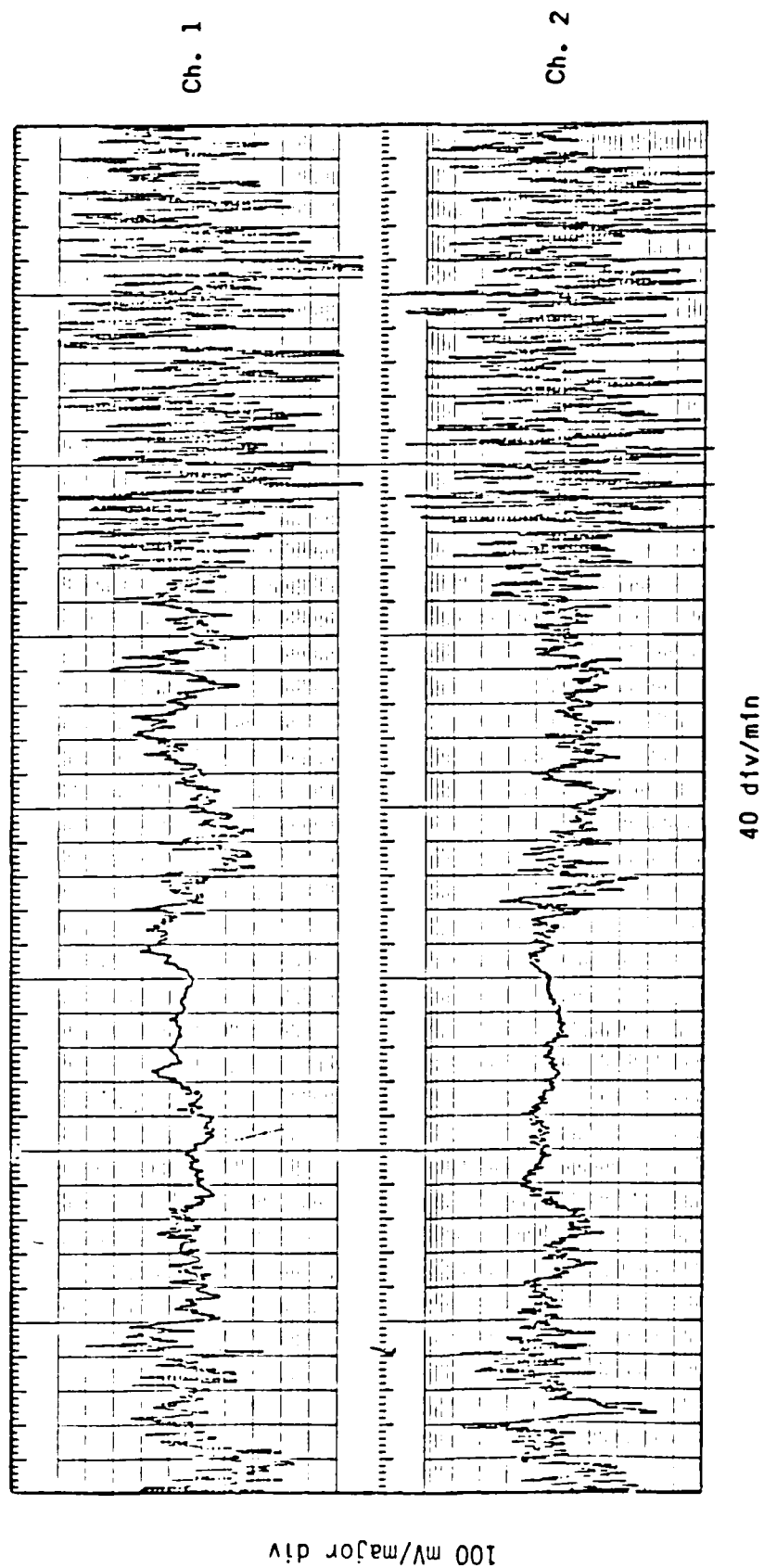
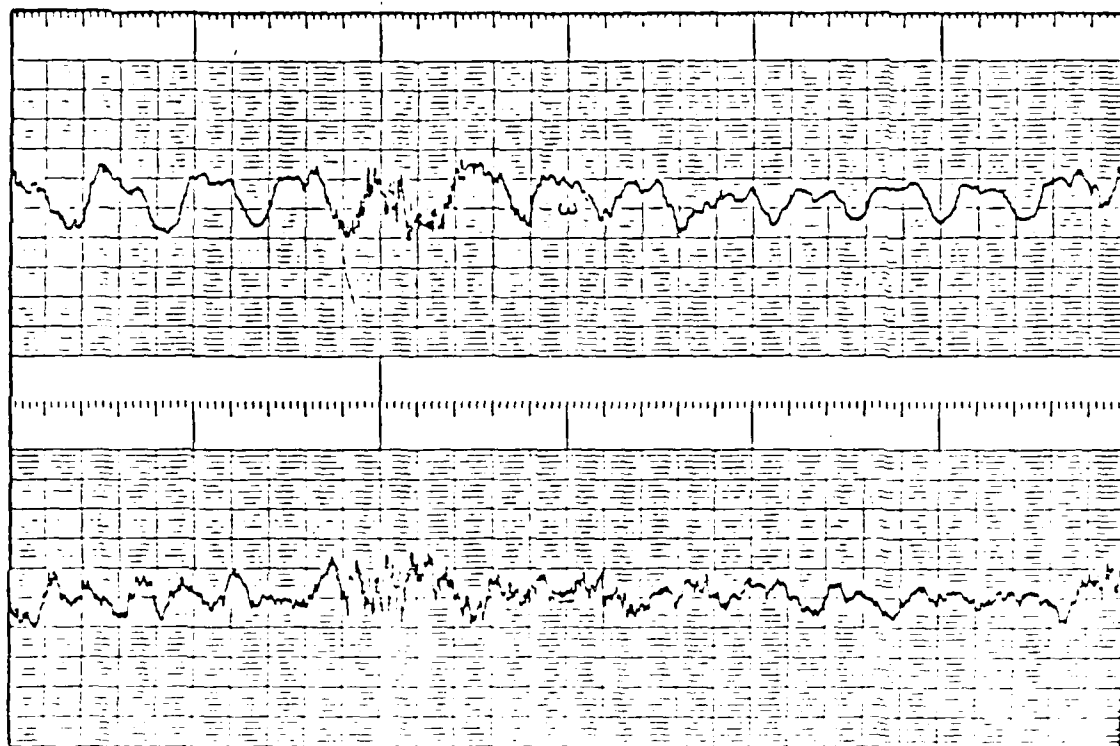


Figure 11 Clutter, varying over a one minute period, detected from 30 meters on 3/27/86.

25 mV/major div



Ch. 1

Ch. 2

40 div/min

Figure 12. Respiration, 50 mV p-p, detected from 60 meters for subject 1 on 3/27/86.

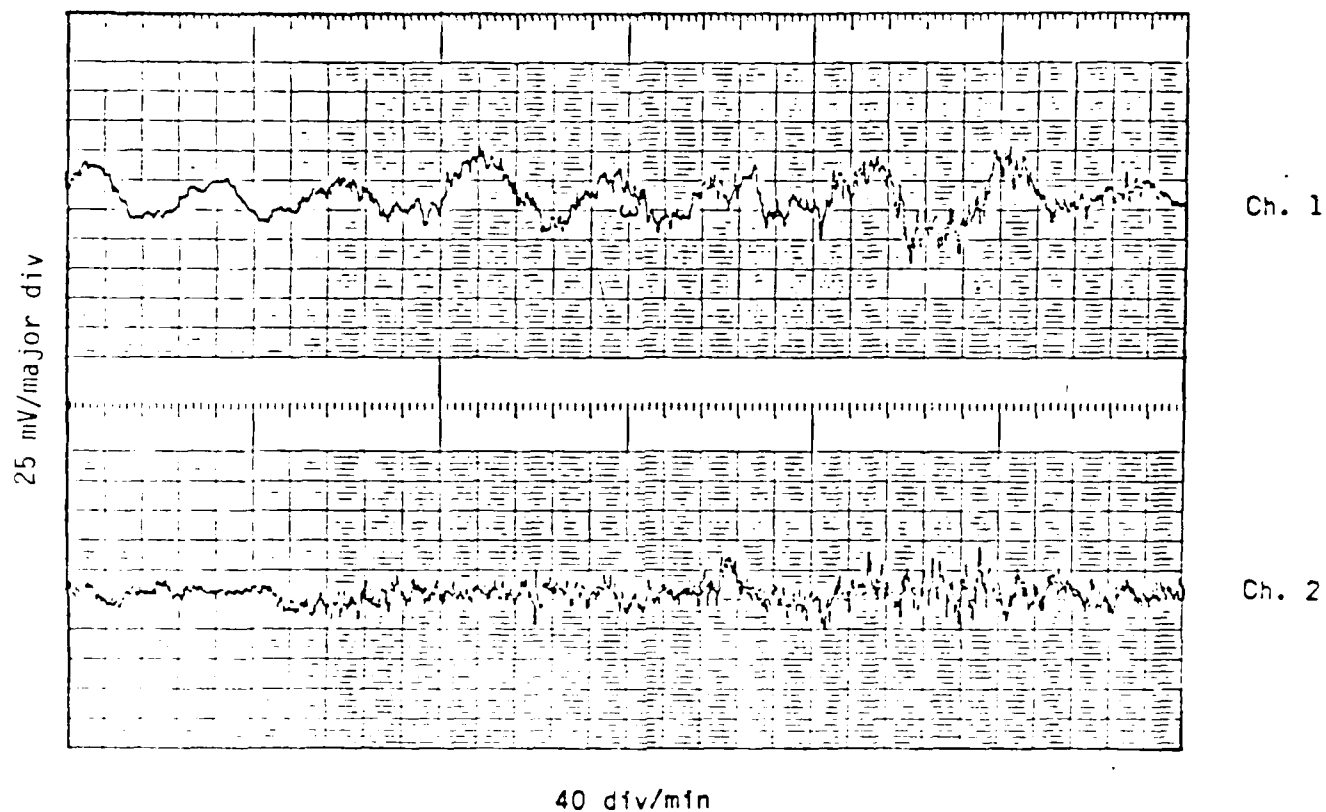


Figure 13. Respiration, 50 mV p-p, detected from 60 meters for subject 2 on 3/27/86.

from the ground in front of the test subject (the antenna beam was broad enough to permit the target to be interrogated). Using the modified antenna aim, respiratory signals were clearly observed for all three subjects tested. Levels of the observed signals were typically 50-100 millivolts, although lower levels were again observed for some body positions.

It is difficult to accurately state the impact of the modified antenna aim on the clutter level because of the wide variations in this level. In one test, clutter from the ground was monitored for a period of eight minutes. For the majority of this period, the clutter level was only 10-15 millivolts, which was lower than the 30-60 millivolts observed on April 1 when the antenna had been aimed directly at the ground. However, there were short periods of time during which the clutter level increased to 40-50 millivolts as shown in Figure 14.

At times, the level of clutter also appeared to be different when a subject was present. In some cases, the level of what appeared to be clutter was as high as 100 millivolts when a subject was present. Thus, it is possible that some of the clutter that had been attributed to ground foliage may have been due to the test subject. Possibilities include wind-induced motion of the clothing and hair, as well as extraneous body motions such as gastrointestinal activity or involuntary muscle activity (twitches). The possibility of part of the clutter observed with the LFD being related to the test subject is something that will be further investigated when the LFD is reevaluated under more controlled conditions.

Tests were also made from 91 and 122 meters to judge the relative performance of the LFD at longer ranges. For the 91-meter tests, it was necessary to employ a range-cell width of 5.5 meters. Even with this large range-cell width, it was possible to detect a strong respiratory signal for the single subject tested as shown in Figure 15. For the 122-meter tests, a larger range-cell width of 7.3 meters was required. A strong respiratory signal was again observed as shown in Figure 16.

The extremely good results from 91 and 122 meters were mainly due to a decrease in the clutter level rather than an increase in the level of the respiratory signal. In fact, as noted earlier, the respiratory signals detected from 91 and 122 meters were weaker than those observed from shorter ranges. Factors contributing to the lower-than-expected clutter levels observed from the longer ranges are not clear. One possibility is that at the longer range

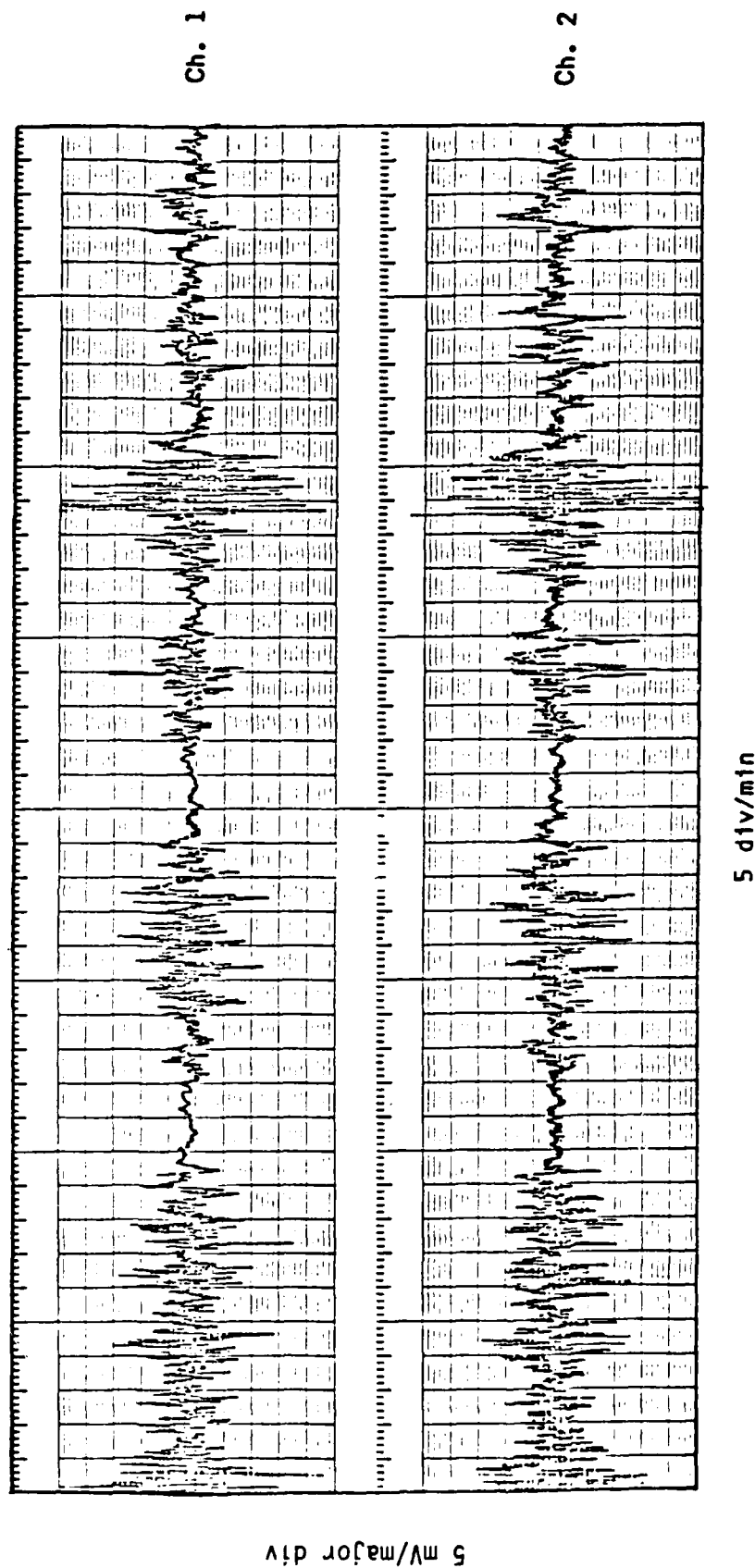


Figure 14. Clutter, varying over a period of eight minutes, detected from 30 meters on 4/4/86.

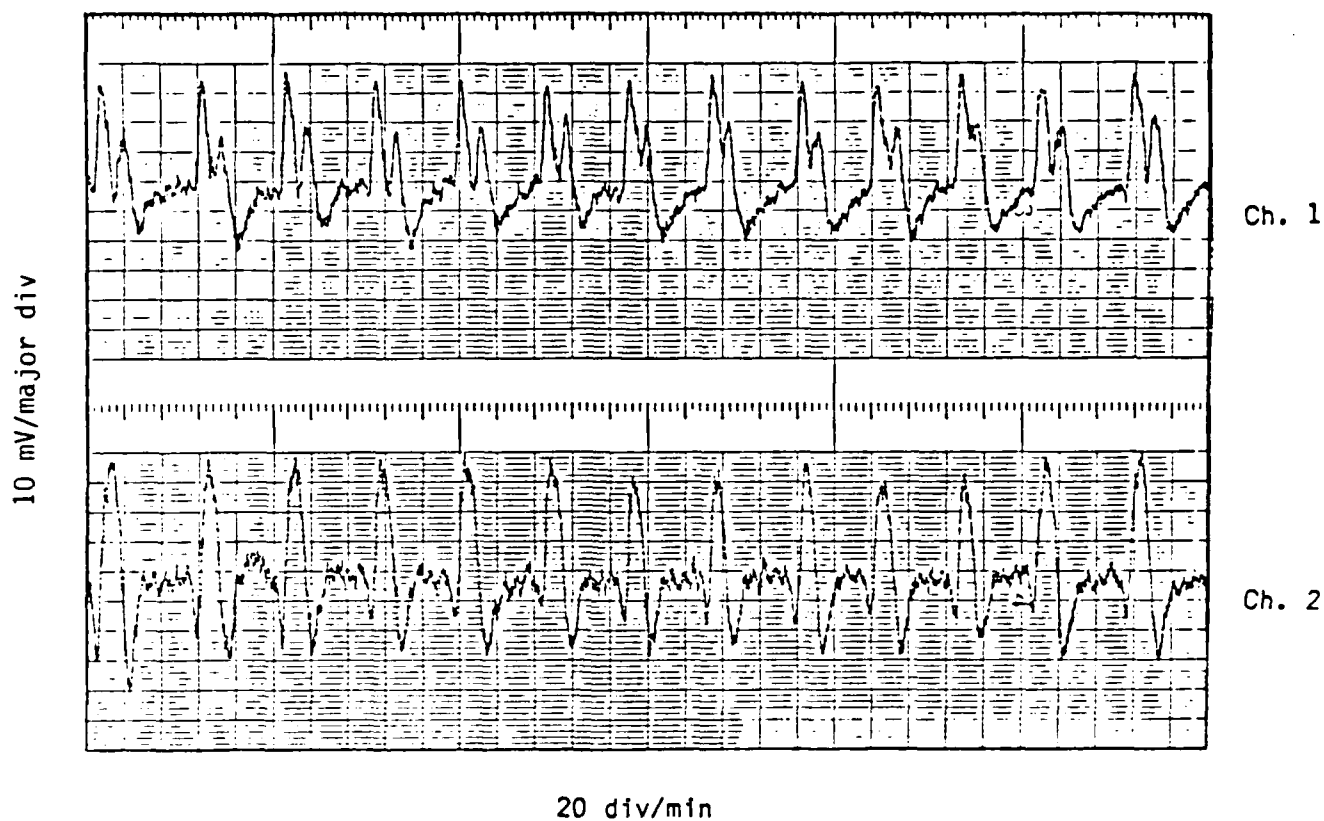


Figure 15. Respiration detected from 91 meters on 4/4/86.

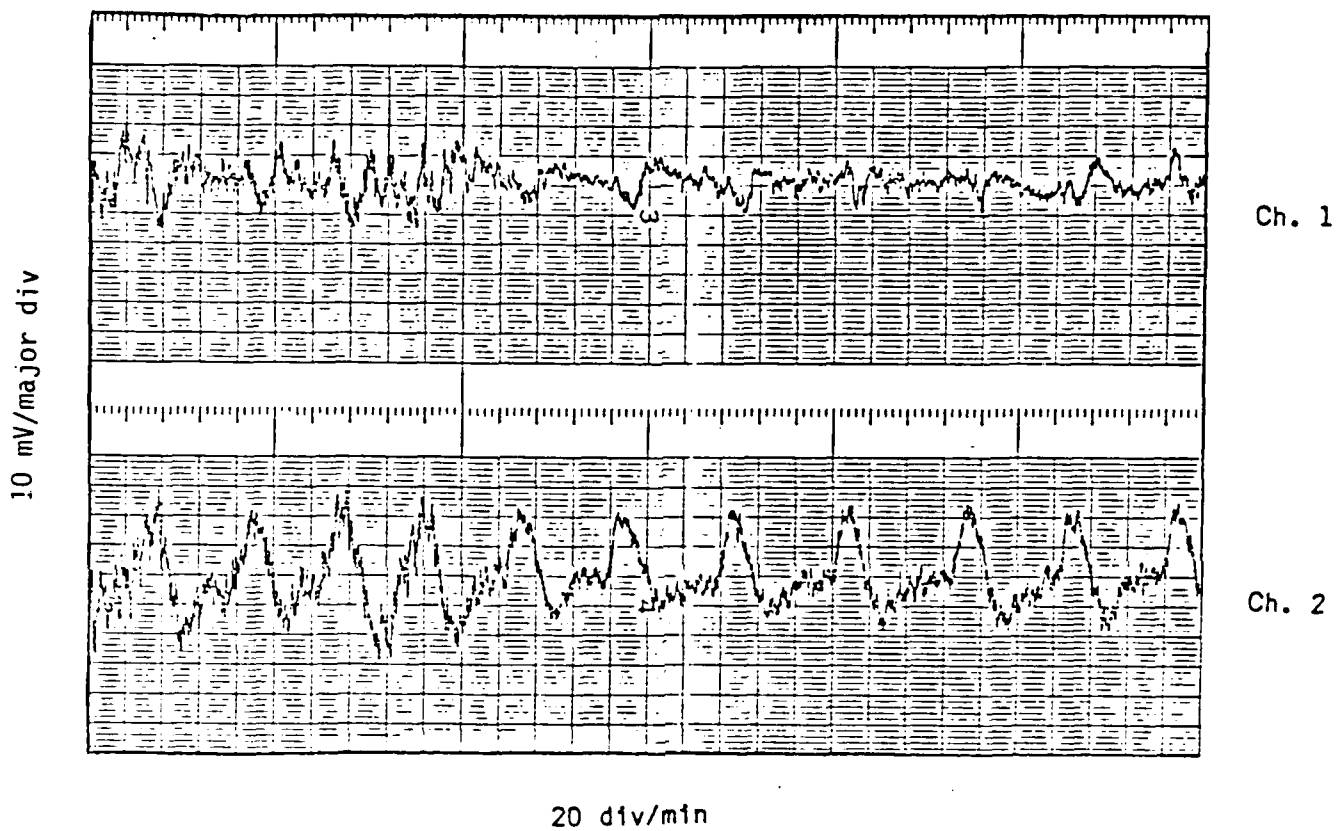


Figure 16. Respiration detected from 122 meters on 4/4/86.

Although improved clutter-suppression is the primary program objective, the LFD's noise floor is also of concern because of the low signal levels that are predicted for operation from extended ranges. From Figure 17, it can be seen that under clutter-free conditions, "strong" respiratory signals should be detectable from ranges greater than 200 meters, "weak" respiratory signals and "strong" cardiac signals should be detectable from ranges up to 65 meters, and "weak" cardiac signals should be detectable from ranges up to 25 meters. These results indicate that even in the absence of clutter, the sensitivity of the LFD must be improved if cardiac signals and weaker respiratory signals are to be detected from long ranges. The sensitivity of the LFD can be improved by lowering its noise floor and/or increasing the level of its respiratory and cardiac signals.

To lower the noise floor, a general-purpose preamplifier in the LFD is being replaced with a new low-noise amplifier. Although noise measurements have not yet been performed, it is estimated the new preamplifier will lower the noise floor by approximately 10 decibels. Also, techniques are being investigated that will permit greater frequency resolution to be employed in processing the output signals from the LFD. Since it appears respiratory and cardiac signals occupy specific and narrow frequency bands, while the system noise is distributed over a broad frequency band, the use of frequency resolution greater than the current receiver bandwidth of 10 Hertz should effectively lower the noise floor. As noted in last year's report, various spectral analysis techniques that will permit greater frequency resolution are under investigation (depending on the spectral characteristics of the clutter observed by the LFD, these techniques may also improve clutter-suppression).

To strengthen respiratory and cardiac components of the LFD output signal, a larger antenna could be used and/or the transmitted power could be increased. It appears that at least a 10 decibel increase in signal levels could be achieved in this manner. If the LFD's transmitted power level is increased (currently 0.100 milliwatts), precautions must be taken to insure that the receiver noise is not simultaneously increased. Implementation of a backup RF-section that permits the transmitted power level to be increased to one milliwatt without degrading the noise floor is currently being considered.

At this time, it is estimated a 20-dB improvement in performance can be practically achieved by lowering the receiver noise floor by 10 decibels and increasing the detected signal strength by 10 decibels. Results are shown in

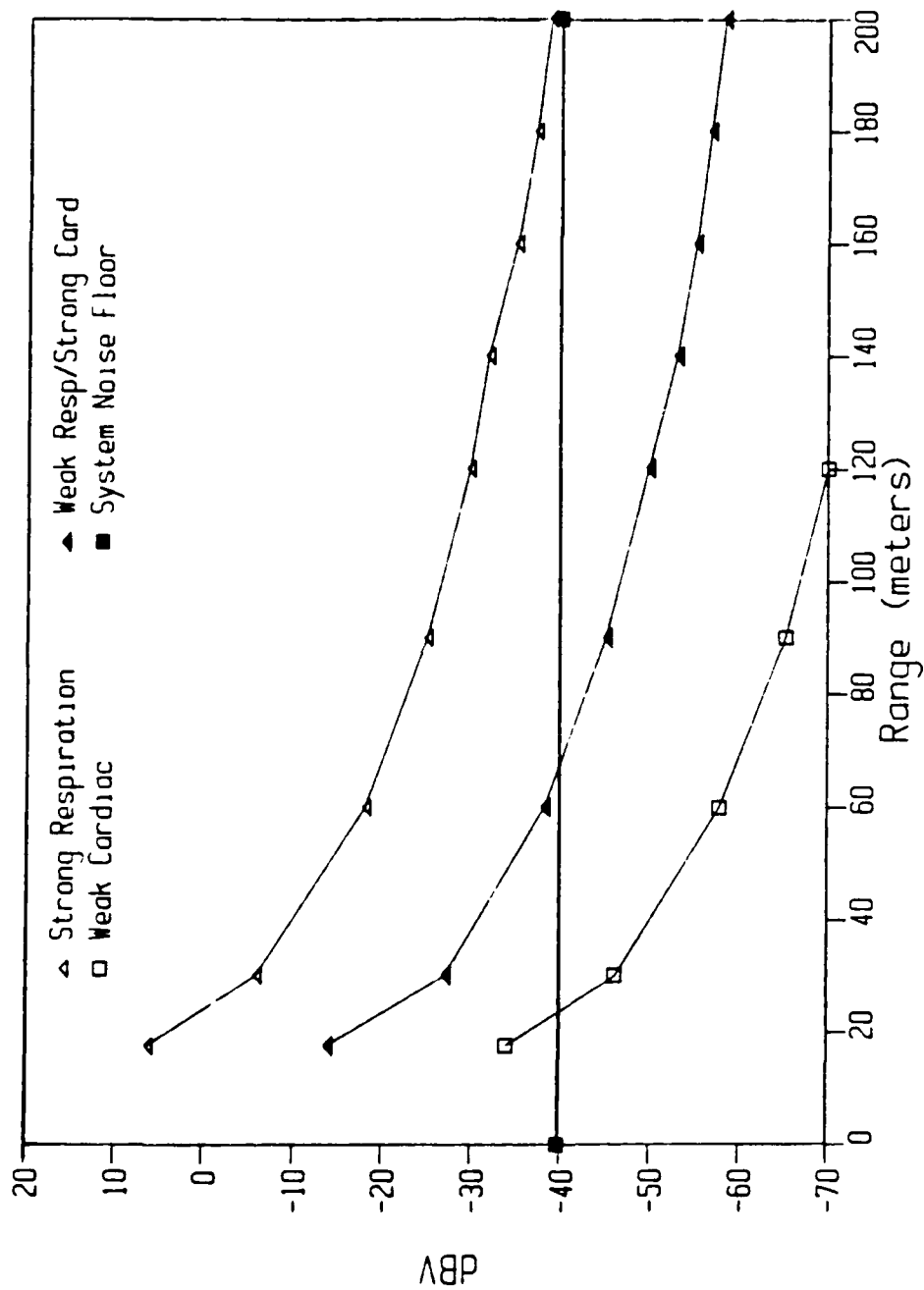


Figure 17. Graph comparing estimated respiration and cardiac signals to observed clutter levels as a function of range.

Figure 18. Based on the radar range equation, a 20-dB improvement in performance would triple the detection ranges indicated in Figure 17. This level of performance should be adequate to insure that clutter, and not system-related noise, is the predominate range-limiting factor encountered during this program year.

The results in Figure 17 do not include the effects of clutter, which field tests have shown has a more profound effect than the internal system noise. For a variety of reasons, it has proven difficult to predict and/or measure the behavior of clutter as a function of range. For example, both the levels and spectral behavior of clutter observed during the field tests varied significantly, making accurate characterization of clutter difficult. In addition, limitations of the receiver used in the field tests prohibited use of narrow range cells when operating at longer ranges. Thus, it is not certain that clutter levels observed in the field tests are representative of levels that would have been observed if one-meter range cells had been employed for all ranges tested.

In Figure 19, typical clutter levels observed during the field tests have been superimposed on the graph of estimated respiratory and cardiac signals. Two points can be noted about the clutter levels observed in the field tests: (1) the observed clutter levels have generally been high enough to completely mask cardiac signals and weak respiratory signals, and (2) strong respiratory signals should be detectable, even in the presence of strong clutter. These conditions were generally observed during the field tests. For example, it was normally possible to detect strong respiratory signals from 61 meters for all subjects tested. However, cardiac signals and weak respiratory signals generally could not be observed from any range.

From the results in Figure 19, it is apparent the clutter-suppression of the LFD must be improved. Because the clutter levels have not behaved in a predictable manner as a function of range or range-cell size, it is difficult to estimate the level of clutter-suppression improvements that can be practically incorporated into the LFD. The primary clutter-suppression approach that has been employed on this program has been reduction of the number of clutter sources in the volume of space interrogated by the LFD. With this approach, the level of clutter-suppression is directly related to system size and complexity. For this reason, the level of required clutter-suppression should be accurately estimated to minimize system demands. For example, using a narrower antenna

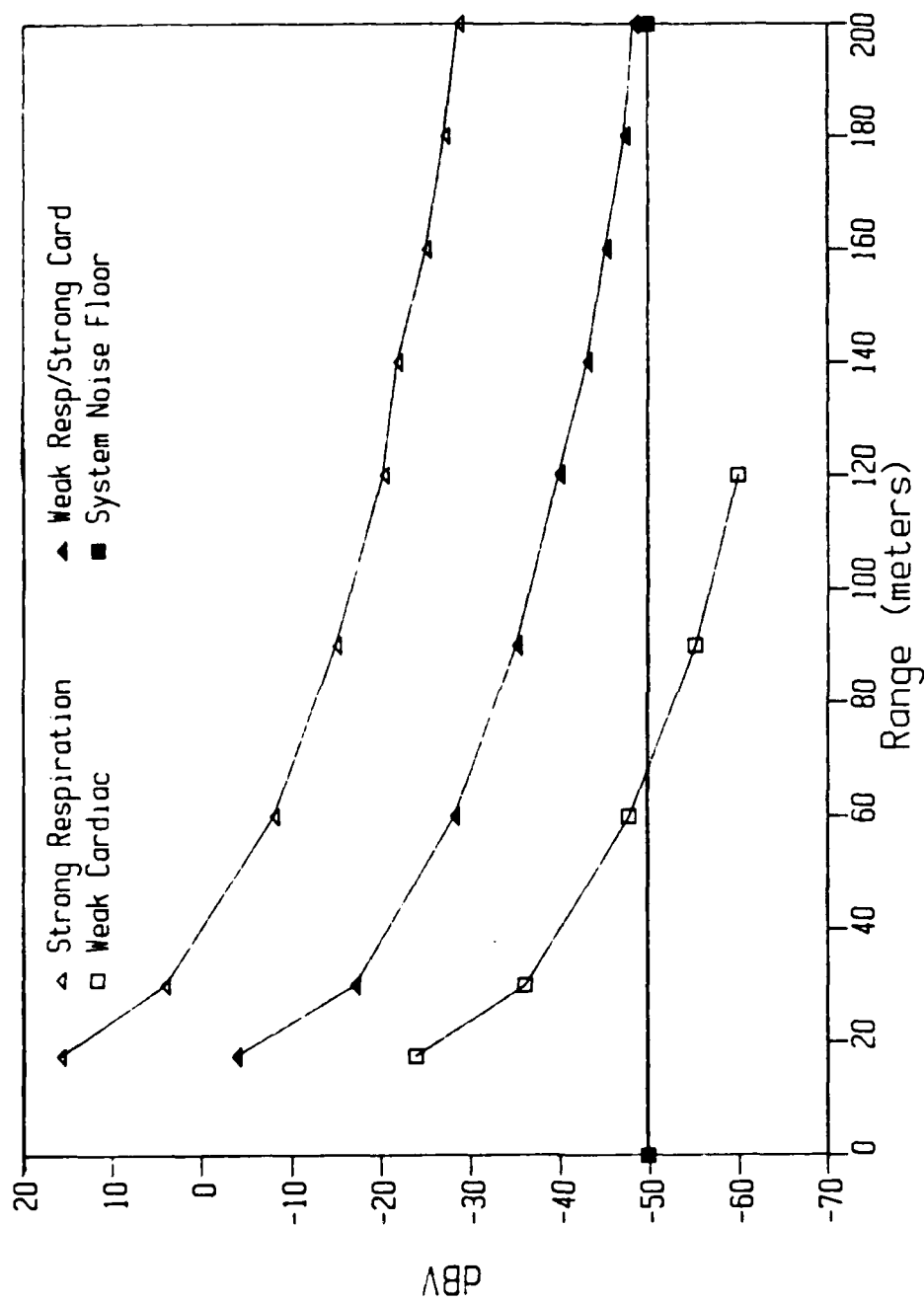


Figure 18. Graph comparing estimated respiration and cardiac signal strengths with system noise floor for the modified LFD system.

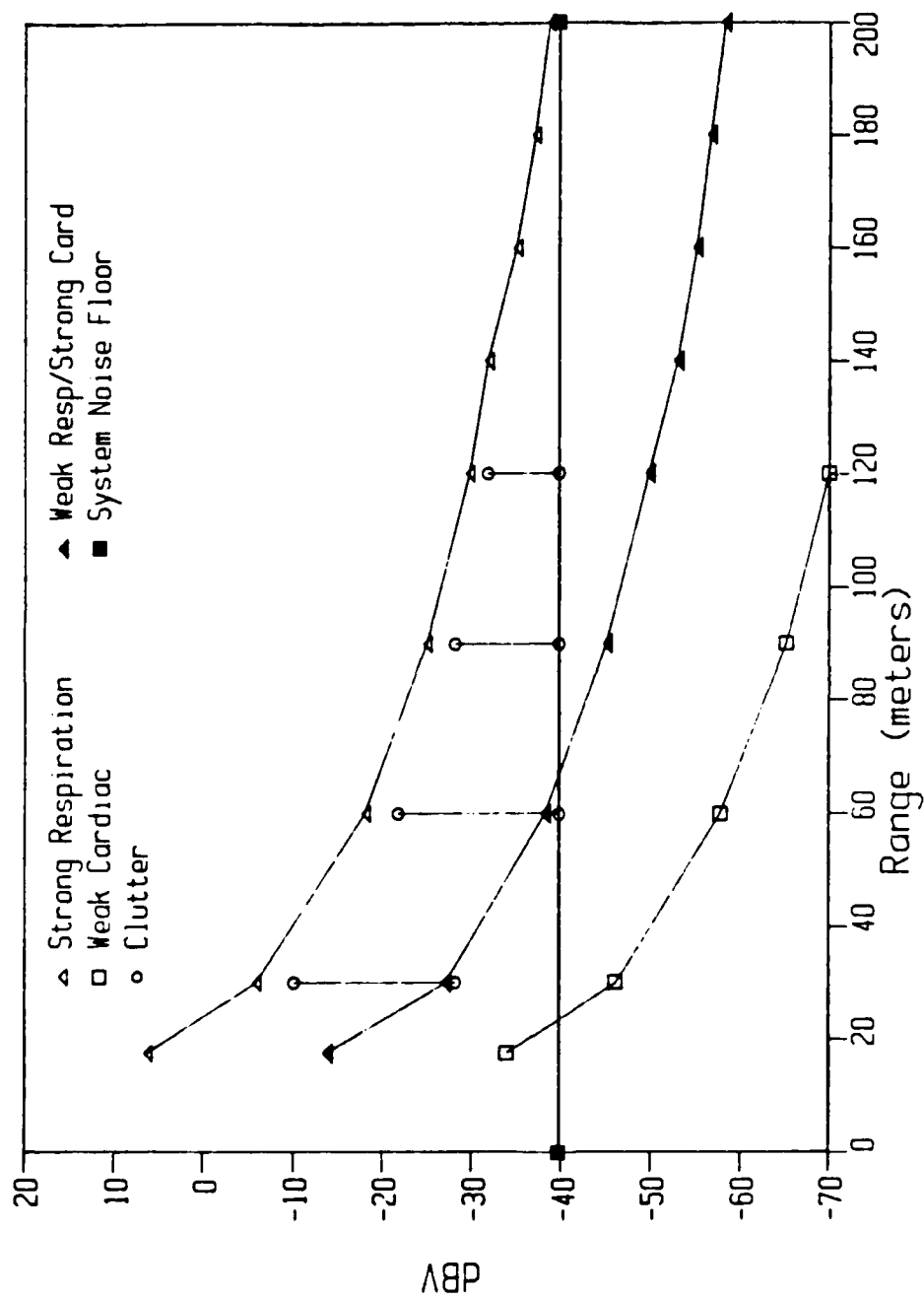


Figure 19. Graph comparing estimated respiration and cardiac signals to observed clutter levels as a function of range.

settings, clutter from sources near the LFD is more effectively suppressed by the range-gating system.

Another possibility is that the test sites used at the longer ranges simply generated low clutter levels (e.g., because of terrain, foliage, wind conditions, or slight differences in incidence angles). To investigate this possibility, the LFD was aimed at a different location at a range of 91 meters. An extremely low clutter level (approximately 10 millivolts) was also observed at the new location. Although not conclusive, this latter result indicated that the LFD was simply detecting a lower clutter level when set for longer ranges. Additional tests will have to be performed to determine if the low clutter levels observed from the longer ranges were due to more ideal system performance or an artifact due to weather, wind, and other conditions.

#### D. Evaluation of Final Year-4 Field Tests

Narrower range cells made possible by the improved range-gating system significantly enhanced the performance of the LFD during the 1986 field tests. For example, respiratory signals were successfully detected from ranges up to 122 meters under conditions nearly identical to those existing in 1985 when signals could not be detected from as near as 15 meters because of severe clutter contamination. Thus, results from the field tests successfully demonstrate the potential capabilities of the LFD. However, because of the variability observed in both the signal and clutter levels, steps must be taken to improve the reliability of the LFD.

One of the most important results of the field tests was the information gained about the level and variability of the respiratory and cardiac signals detected by the LFD. With this information available, the adequacy of the LFD's receiver sensitivity and clutter-suppression capabilities can be conveniently estimated. For example, by combining field test results with previously obtained test results, it was possible to predict the levels of the respiratory and cardiac signals that will be detected by the LFD from different ranges (the predicted levels are directly applicable to the LFD used in the Year-4 field tests, but can be normalized to compensate for differences in antenna gain, transmitted power level, preamplifier gain, etc.). These predicted levels were then compared to noise levels from the LFD in a clutter-free environment to judge the adequacy of the LFD's sensitivity. Results of this comparison are

shown in Figure 17.

Although improved clutter-suppression is the primary program objective, the LFD's noise floor is also of concern because of the low signal levels that are predicted for operation from extended ranges. From Figure 17, it can be seen that under clutter-free conditions, "strong" respiratory signals should be detectable from ranges greater than 200 meters, "weak" respiratory signals and "strong" cardiac signals should be detectable from ranges up to 65 meters, and "weak" cardiac signals should be detectable from ranges up to 25 meters. These results indicate that even in the absence of clutter, the sensitivity of the LFD must be improved if cardiac signals and weaker respiratory signals are to be detected from long ranges. The sensitivity of the LFD can be improved by lowering its noise floor and/or increasing the level of its respiratory and cardiac signals.

To lower the noise floor, a general-purpose preamplifier in the LFD is being replaced with a new low-noise amplifier. Although noise measurements have not yet been performed, it is estimated the new preamplifier will lower the noise floor by approximately 10 decibels. Also, techniques are being investigated that will permit greater frequency resolution to be employed in processing the output signals from the LFD. Since it appears respiratory and cardiac signals occupy specific and narrow frequency bands, while the system noise is distributed over a broad frequency band, the use of frequency resolution greater than the current receiver bandwidth of 10 Hertz should effectively lower the noise floor. As noted in last year's report, various spectral analysis techniques that will permit greater frequency resolution are under investigation (depending on the spectral characteristics of the clutter observed by the LFD, these techniques may also improve clutter-suppression).

To strengthen respiratory and cardiac components of the LFD output signal, a larger antenna could be used and/or the transmitted power could be increased. It appears that at least a 10 decibel increase in signal levels could be achieved in this manner. If the LFD's transmitted power level is increased (currently 0.100 milliwatts), precautions must be taken to insure that the receiver noise is not simultaneously increased. Implementation of a backup RF-section that permits the transmitted power level to be increased to one milliwatt without degrading the noise floor is currently being considered.

At this time, it is estimated a 20-dB improvement in performance can be practically achieved by lowering the receiver noise floor by 10 decibels and

increasing the detected signal strength by 10 decibels. Results are shown in Figure 18. Based on the radar range equation, a 20-dB improvement in performance would triple the detection ranges indicated in Figure 17. This level of performance should be adequate to insure that clutter, and not system-related noise, is the predominate range-limiting factor encountered during this program year.

The results in Figure 17 do not include the effects of clutter, which field tests have shown has a more profound effect than the internal system noise. For a variety of reasons, it has proven difficult to predict and/or measure the behavior of clutter as a function of range. For example, both the levels and spectral behavior of clutter observed during the field tests varied significantly, making accurate characterization of clutter difficult. In addition, limitations of the receiver used in the field tests prohibited use of narrow range cells when operating at longer ranges. Thus, it is not certain that clutter levels observed in the field tests are representative of levels that would have been observed if one-meter range cells had been employed for all ranges tested.

In Figure 19, typical clutter levels observed during the field tests have been superimposed on the graph of estimated respiratory and cardiac signals. Two points can be noted about the clutter levels observed in the field tests: (1) the observed clutter levels have generally been high enough to completely mask cardiac signals and weak respiratory signals, and (2) strong respiratory signals should be detectable, even in the presence of strong clutter. These conditions were generally observed during the field tests. For example, it was normally possible to detect strong respiratory signals from 61 meters for all subjects tested. However, cardiac signals and weak respiratory signals generally could not be observed from any range.

From the results in Figure 19, it is apparent the clutter-suppression of the LFD must be improved. Because the clutter levels have not behaved in a predictable manner as a function of range or range-cell size, it is difficult to estimate the level of clutter-suppression improvements that can be practically incorporated into the LFD. The primary clutter-suppression approach that has been employed on this program has been reduction of the number of clutter sources in the volume of space interrogated by the LFD. With this approach, the level of clutter-suppression is directly related to system size and complexity. For this reason, the level of required clutter-suppression should be accurately

estimated to minimize system demands. For example, using a narrower antenna beamwidth to reduce clutter would require using a larger antenna. Thus, the antenna beamwidth cannot be arbitrarily reduced without sacrificing system portability. Similarly, decreasing the range-cell size should reduce clutter but will also increase the number of range cells the receiver in the LFD must be able to interrogate which would require the use of a more complex receiver.

Attempts to define the improvements associated with reduced antenna beamwidths and range-cell widths have been inconclusive. For example, if it is assumed the clutter sources are uniformly distributed, halving the range-cell width should reduce the clutter voltage by approximately 3 decibels. In two separate tests to determine the impact of reduced range cells, the clutter was reduced by 5-7 decibels when the range-cell size was halved, instead of by the expected 3 decibels. These results may be attributable to the large fluctuations that typically have been observed with clutter. However, they may also indicate that clutter sources are not uniformly distributed. In the latter case, there may be a limit to the clutter-suppression improvements that can be achieved through reduced interrogation volumes unless the volumes can be made small enough to include only the target of interest. Because of the difficulty of predicting the impact of improving existing clutter-suppression capabilities, additional measurements will be made with the current LFD before any major hardware changes are contemplated.

#### E. Signal Processing Investigations

Detection theory provides methods that can be applied to a particular signal-noise process to derive and characterize a detector that is optimum for that process. Generally, this optimum detector will decide between different detection hypotheses by comparing a quantity called the likelihood ratio to a specific detection threshold [7]. The detection threshold, which can be based on different criteria depending on the selected definition of good detection performance, represents a compromise between performance measures such as detection probability and false alarm probability.

The suitability of an optimum detector for a particular detection task will be dependent on the quality of the information available about the signals and noise being processed and about costs associated with possible detection decisions (correct as well as incorrect). The more specific the available

information, the "better" the optimum detector that can be implemented. However, for a given set of conditions, the resulting optimum detector represents the best detector that can be implemented based on the specified performance criterion.

The concept of a likelihood ratio detector can be used to confirm that a matched-filter detector is optimum for the signal-known-exactly (SKE) case (this example was used in the Third Annual Technical Report). The reliability (i.e., the detection probability and the false alarm probability) of the matched-filter detector for this case was found to be directly related to the detectability index, which was determined by the SNR and observation period. As expected, for low SNR cases, reliable performance of the matched-filter detector required lengthy observation periods. That is, for the SKE case, the use of signal processing techniques such as the optimum detector can be used to enhance detection performance when signals are weak or noise is strong, but only at a cost of increased observation times.

For the LFD, the task of the detector is to decide between the hypotheses that: (1) the system output contains only noise (no life indications detected) or (2) the system output contains a signal-plus-noise (life indications detected). These hypotheses may be referred to as  $H_0$  and  $H_1$ , respectively [7]. If the output of the LFD is denoted as  $y(t)$ , and if  $n(t)$  and  $s(t)$  are used to denote the noise and signals, respectively, the detection hypotheses can be expressed as follows:

$$H_0 : y(t) = n(t) \quad \text{"noise-only"}$$

$$H_1 : y(t) = s(t) + n(t) \quad \text{"signal-plus-noise"}.$$

For optimum detection, it has been established that the likelihood ratio will be used to decide between  $H_0$  and  $H_1$ . The likelihood ratio, which will be denoted as  $L(y)$ , can be defined in terms of the conditional probability density functions of the signals and noise being processed. Thus, in terms of the likelihood ratio, the detection rule becomes:

$$\text{Choose } H_0 \text{ if } L(y) = p_0(y) / p_1(y) < L_0 ,$$

else choose  $H_1$ ,

where  $p_0$  and  $p_1$  represent conditional probability density functions for  $y$ , and  $L_0$  represents the desired detection threshold.

Based on this information, it can be seen that the optimum detector for the LFD will consist of two parts: (1) a processor that outputs the likelihood ratio or (equivalent parameter) and (2) a decision unit that compares the likelihood ratio to a suitable detection threshold (see Figure 20). The detection threshold input to the decision unit will significantly impact the performance of the optimum detector. A low detection threshold will improve the detection probability but will worsen the false alarm probability. Conversely, a high detection threshold will improve the false alarm probability but worsen the detection probability. Thus, the ability to appropriately set the detection threshold is a key step to achieving a specified level of detection performance.

In some applications, probability and cost information about the detection hypotheses can be used to establish a suitable threshold level (Bayes Criterion [8]). In applications such as the LFD, where useful probability and cost information are generally not available, the Neyman-Pearson Criterion can be employed [9]. For this criterion, the false alarm probability is normally specified and the threshold level is then set to maximize the detection probability without exceeding the specified false alarm probability. With this approach, the detection probability that can be achieved will be determined by factors such as the signal-to-noise ratio, observation period, and other parameters controlling the performance of the likelihood ratio processor. Thus, to insure good performance of the optimum detector, the likelihood ratio processor must be designed to take advantage of any available information about the signals and noise.

To fill this important need, spectral studies are being performed on the respiratory signals, cardiac signals, and clutter (predominate noise mechanism) from the LFD. Results of the spectral studies that have been completed show that the signals from the LFD are nearly periodic for short observation periods, and approximate limits have been established for the frequency bands occupied by the signal spectra. The spectral studies have also shown that over the estimated signal frequency bands, the noise is random with an autoregressive power spectrum (although different results may be found for other types of clutter sources).

In principle, given this information about the signals and noise, an

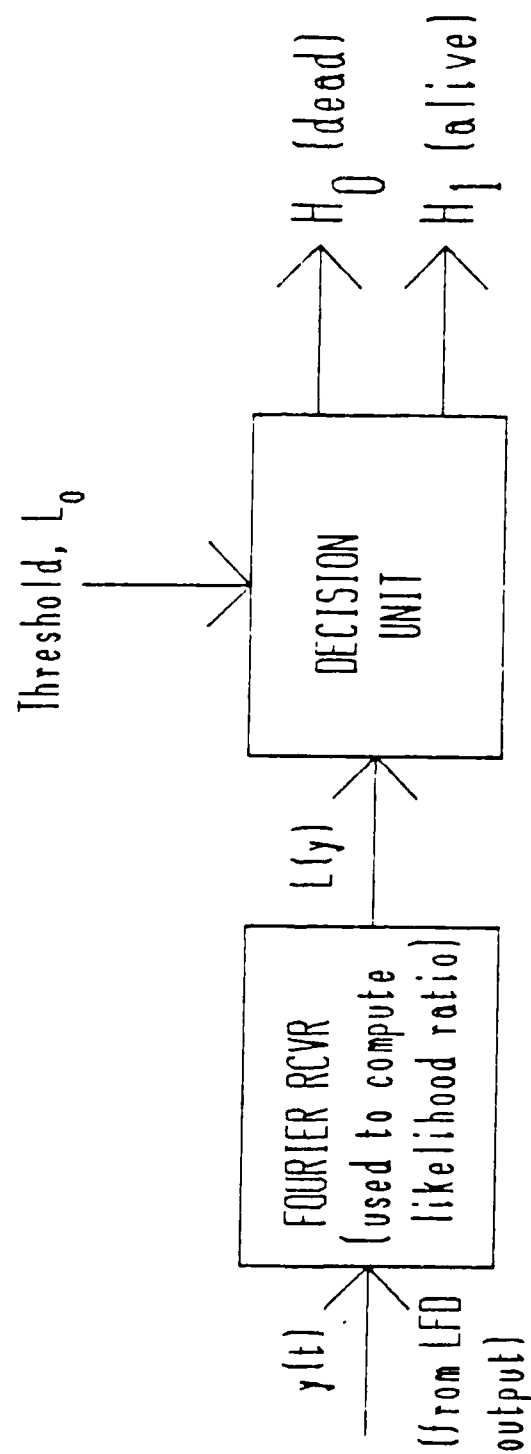


Figure 20. Block diagram of optimum detector.

optimum detector for the LFD can be derived. However, for this particular signal-noise model, as in many other practical detection situations, implementation of an optimum detector is numerically very complex. Thus, a numerically-efficient approximation to the optimum detector is sought. A near-optimum detector can be achieved by simplifying the derived optimum detector or by empirically selecting a processor that is suspected to be a reasonable approximation of the optimum detector. In either case, the suitability of the selected near-optimum detector can be evaluated by comparing its performance to that of the derived optimum detector (e.g., using computer simulations).

Based on spectral studies that have been performed on signals from the LFP, a narrowband signal in wideband noise is one possible signal-noise model being considered for the LFD. The optimum detector for this signal-noise model can be approximated very closely by much simpler structures. An especially convenient structure is the Fourier Receiver which can be implemented with the numerically-efficient Fast-Fourier Transform [10,11]. In its most general form, the Fourier Receiver performs a frequency-domain transformation which measures energy in a specified range or ranges of frequencies. If the Fast-Fourier Transform (FFT) is used for the frequency-domain transformation, spectral energy at a series of discrete frequencies will be computed. The measured spectral energy at each discrete frequency (this energy can be due to the signal-plus-noise or to noise-only) can be divided by the estimated noise-only spectral energy to approximate the desired likelihood ratio. The resulting ratio can in turn be compared to a suitable threshold level so the required detection decision can be made.

The Fourier Receiver is very general and can be optimized for different situations through proper choice of system parameters. For example, in one extreme, it can become a contiguous-filter bank which is optimum for detection of narrowband signals (e.g., sinusoids) in noise [10,11], while at the other extreme, it becomes an energy detector which is optimum for detection of signals of completely unknown form [12,13]. It can also be optimized for signals between these two extremes, which likely includes those encountered with the LFD. The suitability of the Fourier Receiver for the detection problem posed by the LFD is further examined in the following discussion.

Because of the nearly-periodic behavior of the signals from the LFD over short observation periods, spectral components corresponding to the fundamental respiratory and cardiac frequencies can be modeled as narrowband signals in wideband noise. The matched-filter detector derived for the SKE case would be a

good solution to this problem if the exact frequency of the signals from the LFD were known. However, without accurate frequency knowledge, it is clear the matched-filter detector is not a practical solution. It has been shown that a contiguous-filter bank can be used to overcome uncertain frequency information when detecting narrowband signals in wideband noise [14].

For the LFD application, a contiguous-filter bank would include a set of narrowband filters, each having a different center frequency, that collectively cover the information band of interest. With this approach, the impact of frequency uncertainties is reduced since all possible frequencies are examined. The bandwidth of each filter in the filter bank can be matched to that of the narrowband signals being detected. Thus, each individual filter approximates a matched filter which insures good detection performance.

Each filter in the filter-bank can be followed by a square-law detector, a combiner (which may be linear or nonlinear), and an integrator. If the output of the LFD is processed through an appropriately designed contiguous-filter bank, any existing narrowband signals within the known information band will appear at the output of the integrator in one of the filter channels. The output of each integrator can be compared to a suitably established threshold to decide between the two previously discussed detection hypotheses (procedures for obtaining the detection threshold are discussed later in this part of the report).

For the narrowband signal-in-wideband noise model, the preceding discussion indicates the contiguous-filter bank represents a suitable detection approach. However, the selection of this detection approach was not based on all the information available for the signals from the LFD. Additionally-known signal information is now considered to further judge the suitability of the Fourier Receiver-based optimum detection approach.

Spectral studies have shown that in addition to containing components corresponding to the fundamental respiratory and cardiac frequencies, spectra of the LFD's output contain components at harmonics of the fundamental signal frequencies. For respiratory signals, the harmonics are typically 10 to 20 decibels lower than the fundamental respiratory component. Thus, modeling of a respiratory signal as a narrowband signal is valid since only a small portion of the respiratory information is contained in the harmonic terms, and the Fourier Receiver should prove to be an effective approach for detecting respiratory signals.

Cardiac signals from the LFD display a significant harmonic structure reflective of the more impulse-like behavior of cardiac function. As shown in the numerous examples in the Third Annual Technical Report, 6 to 8 harmonic terms typically were observed in the spectra of cardiac signals from the LFD. More importantly, the second, third, and fourth harmonic terms were often comparable in strength to the fundamental cardiac component. Thus, modeling the cardiac signal as a narrowband signal in an information band corresponding to the range of possible cardiac rates (e.g. 0.5-3 Hz, corresponding to 30-180 beats per minute), is not the best detection approach since useful cardiac information contained in the harmonic terms can be discarded. This could be especially unwise if the noise (clutter) in the frequency band occupied by the harmonic terms is lower than the noise near the fundamental cardiac frequency.

One solution to this problem is to increase the information bandwidth to include the harmonic terms (easily accommodated with the Fourier Receiver). This would be equivalent to modeling the cardiac signal as a group of narrowband signals, each having an unknown frequency. The contiguous-filter bank is a reasonable detector for this signal-noise model since a narrowband-filter would essentially be provided at every possible frequency within the information band. However, several possible conditions must be considered to determine if such a model is reasonable for detection of cardiac signals.

A potential problem with modeling the cardiac signal as a group of narrowband signals is that the harmonic relationship between the individual signals is not taken into consideration. That is, although a narrowband filter may provide near-optimum detection for any individual harmonic of the cardiac signal, the overall detection performance may suffer if the harmonic relationship is not also considered. The autocorrelation function is one method that has been investigated to determine its usefulness for detecting harmonically-related signals (or periodicities). In principle, the autocorrelation function should be well-suited for this task [15]. However, the impact of strong noise components has made it difficult to obtain good results with the autocorrelation function, and further tests will have to be performed to determine if more appropriate parameter selection or averaging can be used to obtain improved results.

FFT-based techniques might also prove useful for detecting harmonically-related signals if the computed FFTs could be further processed in an appropriate manner. For example, depending on the relative SNR for the

individual harmonic components present in the FFT, summing or averaging of harmonically-related components might be useful for enhancing detection performance. The FFT could also be correlated against stored spectral replicas that exhibit the expected harmonic behavior. Since a variety of possible signal spectra could be stored, it appears a very powerful detector could be implemented in this manner. With either of these suggested approaches for detecting harmonically-related signals, the actual signal frequencies would not be known. Thus, all possible harmonic combinations in the specified information band would have to be tested. However, the cost of testing the possible combinations would be computational time, and not actual observation time.

A second possible problem of modeling the cardiac signal as a group of narrowband signals is any variability that might occur in the cardiac rate. Variability in the cardiac rate broadens the individual spectral components. This broadening effect becomes more pronounced as the harmonic number is increased since the variability is multiplied by the harmonic number. For short time-periods, spectral broadening is minor and individual spectral components can be clearly observed as shown in Figure 21 (from the Third Annual Technical Report). For long observation periods, variability in the cardiac rate may broaden spectral components so significantly that the individual components overlap in frequency, resulting in smearing of the spectrum over the cardiac information band.

If variability in the cardiac rate produces a smeared spectrum, the contiguous-filter bank is still a reasonable detection approach since the filter outputs would represent the spectral distribution of the signal energy during the specified observation period. However, in this situation, it appears a filter bank with many narrowband filters would not offer any improvement in detection performance over that which could be achieved using only a few broadband filters (essentially energy detection). In addition, since an energy detector is extremely convenient to implement, it may represent a more practical detection approach when the signal energy occupies a large portion of the information band. Since the energy detector represents one extreme form of the Fourier Receiver, the Fourier Receiver represents a reasonable detection approach even if the cardiac signal from the LFD must be modeled as a broadband signal.

The preceding discussion indicates that implementation of an effective detector is contingent upon the availability and wise use of suitable

information about the signals and noise. The contiguous-filter bank and the energy detector, which represent opposite extremes of the Fourier Receiver, both show promise for use in the LFD. In situations where uncertainty about the signal spectrum is high, the energy detector may represent the best choice in a detector. If the signals are known to be narrowband or to display distinct harmonic behavior, the contiguous-filter or other more sophisticated techniques capable of taking advantage of spectral differences between the signal and noise may prove useful.

In some applications, detailed information about the signals and noise is not available in advance, making it difficult to derive an effective optimum detector. In such cases, a reasonable (although not necessarily optimum or even desirable) approach is to estimate various signal and/or noise parameters, then use the estimated parameters to design an appropriate detector. Such approaches are generally described as adaptive processes. Significantly, since estimation of the signal-noise parameters is not perfect, especially for the important low SNR case, some performance penalty is inevitable when adaptive processing is used. That is, if the information being estimated was actually known, the optimum detector that could be implemented using the known information would be better than the adaptive processor based on the estimated information. This raises the controversial question of whether it is better to: (1) employ a nonadaptive detector optimized for the case of incomplete a priori parameters, or (2) employ an adaptive detector based on estimated signal parameters.

The answer to this question may be dependent on the characteristics of the signal and noise being processed. If the signals and noise do not vary significantly, and can be well-characterized on an a priori basis, it appears an adaptive processor has little to offer over a suitably-derived nonadaptive processor (with the possible exception of convenience). To illustrate this point, detection of a narrowband signal of unknown frequency in wideband noise can be considered. With a sufficiently high SNR, good detection performance could be achieved by using an adaptive filter that estimates the frequency of the signal, then matches its center frequency to the signal frequency. However, good performance also could be achieved by simply using an FFT-processor to examine the signal-noise spectrum, then checking the spectrum for the peak associated with the narrowband signal. In this case, it appears the observation period required to collect data for performing an appropriate FFT is analogous to the learning phase the adaptive filter would have to go through before its

center frequency was accurately set.

If the signals and/or noise vary significantly (making it difficult to characterize the signals and noise a priori), but can be accurately estimated for the selected observation period, it appears adaptive processors can be useful when compared to a nonadaptive processor that cannot compensate for signal-noise variability. However, in this latter case, poor detection performance may result from the use of adaptive processing if the signal-noise estimates are not accurate (probable if the SNR is low).

In the Fourier Receiver being implemented for the LFD, adaptive techniques will be used to set the detection threshold based on the estimated clutter spectrum. It is conceivable that detection threshold levels could be established based on a priori estimates of clutter characteristics. However, because of the significant short-term variations that have been observed in the clutter, it is doubtful good detection performance could be obtained based on such a priori estimates. With the planned adaptive technique, the detection threshold will be lowered when clutter is low, resulting in a higher probability of detection. Conversely, if clutter is high, the detection threshold will be increased to maintain the specified false alarm probability.

Two different techniques are being considered for estimating the clutter (noise-only) spectrum required for adaptively setting the detection threshold. In one of these techniques, the output of the FFT-processor would be smoothed and used as an estimate of the noise-only spectrum. In the event that a signal is not present, the smoothed spectrum will certainly represent a reasonable estimate of the noise-only spectrum. If a signal is present, the smoothed spectrum will still provide a reasonable estimate of the noise-only spectrum provided the signal is sufficiently narrowband. This approach is currently being implemented.

If the signal is too wideband to permit the noise-only spectrum to be accurately estimated from the signal-plus-noise spectrum, an alternative technique has been identified. In this alternative technique, spectral estimates will be computed using information from the range-cells surrounding the cell containing the target (casualty). Since the surrounding range-cells should contain only clutter, their spectral estimates should represent a reasonable estimate of the noise within the target range-cell. This approach will require a sophisticated receiver capable of interrogating multiple range cells (preliminary plans for such a receiver were developed during Year-4 of

this program). However, any additional receiver complexity will be offset by the simplicity of the energy detector that could be employed in this situation.

Another adaptive processing technique investigated during the fourth program year was the normalized least squares lattice filter (implemented on an IBM-PC desktop computer) [16]. This filter uses a least square minimization algorithm to estimate signal parameters referred to as predictor coefficients. These signal parameters can be used to predict the current value of a process from past values of the process. The difference between the predicted current value and the actual current value is the prediction error.

Siegel used this filter to process the output of a microwave heart monitor [17]. For that application, it was assumed that the input process (the output of the heart monitor) was short-term stationary between heartbeats and that the heartbeats were nonstationary. Under these assumptions, the adaptive filter will whiten the signal between heartbeats. When a heartbeat occurs, the predicted value for the input process will be a continuation of the whitened stationary process observed between heartbeats. The difference between this predicted value and the true value (the heartbeat) will therefore be significant so that a large prediction error is an indication of the occurrence of a heartbeat.

Siegel found the lattice filter to be effective in processing the output of the microwave heart monitor. However, before it is assumed the lattice filter is appropriate for use in the LFD, differences in the estimation problem faced by the heart monitor and the detection problem faced by the LFD should be considered. The heart monitor was used to estimate the frequency of a heartbeat signal in the presence of an interfering respiratory signal. Thus, the task of the heart monitor is to estimate the frequency of a narrowband signal (cardiac) in the presence of narrowband noise (respiration).

Although time-based waveforms of the composite respiratory-cardiac signal from the heart monitor displayed heavy corruption due to its strong respiratory-related content, spectral studies have shown that respiratory and cardiac signals largely occupy different frequency bands. Thus, the actual SNR in the cardiac information band was probably quite good. Conversely, for the LFD, respiratory and cardiac signals are both considered to be contaminated by wideband noise in the form of clutter, and in most cases, the SNR observed by the LFD is low.

Because of the spectral separation between the respiratory and cardiac

frequency bands, the adaptive lattice filter employed in the heart monitor was able to suppress respiratory-related effects and permit an "improved" heartbeat signal to be observed in the time-domain. In suppressing the effects of the low-frequency respiratory signal, the lattice filter also partially suppressed the fundamental component of the cardiac signal (and possibly the first few harmonics of the cardiac signal). Because the higher-order harmonic components of the cardiac signal were strong, the output of the adaptive filter was a reasonably strong cardiac signal. However, since some of the information present in the cardiac band was essentially discarded, actual detection performance was below that which would have been achieved using an approach such as the Fourier Receiver.

The preceding, sometimes intuitive, discussion of possible detection approaches for the LFD has examined several key points. From detection theory, the concept of an optimum detector based on a likelihood ratio receiver has been reviewed. For the SKE case, the matched-filter detector, which can be implemented in a number of convenient forms, is known to be optimum. When uncertainty exists about the signals and noise to be processed, optimum detectors can still be implemented based on available information about the signals and noise. However, in such applications, the optimum detector generally is very complex and approximations to the optimum detector must be used because of the practical limitations of available computers. Current efforts on this program include implementation of a near-optimum detector based on the concepts of the Fourier Receiver.

In cases where a detector of limited capabilities must be implemented because of poor signal and noise information, it appears detection performance can be improved with adaptive techniques, provided the SNR is high enough to permit reasonable estimates of the signal and/or noise characteristics. For the LFD application, the ratio of suspected signal-plus-noise power spectra to noise-only power spectra will be used to compute the required likelihood ratio. The information available about the signals and noise is sufficient to suggest that the processor used to obtain the required power spectra need not be adaptive. Several adaptive spectral estimation techniques were, in fact, investigated during the fourth program year (e.g., autoregressive spectral estimation). The adaptive techniques performed well when the SNR was high but did not work any better than a conventional FFT-processor when the SNR was low. Although the FFT-processor may not need to be adaptive, adaptive techniques

should be employed to set the threshold used in each detection decision because of the significant clutter level variability that has been observed. A procedure for adaptively setting the detection threshold based on estimates of the noise-only spectrum is currently being implemented.

### III. CONCLUSIONS

Investigations during the fourth year of this program were both productive and informative. The successful results obtained from a range of 122 meters (400 feet) in April 1986 are believed to be a realistic indicator of the LFD's excellent potential for achieving detection ranges in excess of 100 meters, provided clutter can be adequately controlled. For controlling clutter, the consistent results obtained for strong respiration signals from a range of 61 meters (200 feet) indicate an FM-CW range-gating approach can be used to effectively suppress clutter. However, from results obtained for weak respiration signals and for cardiac signals, it is apparent further improvements must be made to the FM-CW system so that even greater clutter-suppression can be attained.

Improved clutter-suppression has been the focus of research efforts for the past two years. Based on test results during this two-year time period, progress might appear arduous. In actual fact, progress has been excellent but several factors have served to mask the progress that has been made. The most significant of these factors has been the consistent underestimation of the enormous clutter problem faced by the LFD. Because of this underestimation, many of the clutter-suppression features that have been incorporated into the LFD have not been as effective as needed, even though they actually represented significant improvements in performance.

The difficulty encountered in obtaining reliable clutter information was a direct result of the uniqueness of the LFD application. For example, no published clutter data was found that was applicable to this problem. In general, most moving target radar systems examine doppler frequencies that are significantly higher than the frequencies generated by ground clutter. Conversely, the respiratory and cardiac signals of interest to the LFD occur at frequencies where the ground clutter spectrum peaks. Because of the absence of useful clutter information, clutter measurements have evolved into an integral part of this program effort.

To be relevant, clutter information must be measured as a function of parameters such as range, range-cell size, terrain, and seasonal conditions. Instrumentation suitable for making clutter measurements under this variety of conditions is not easily obtained. In fact, the only instrument that has proven

to be of any use for the required clutter measurements has been the LFD itself. Even then, the measurements that can be performed are limited by the capabilities of the LFD, making it difficult to use an existing system to predict the performance of an improved system. For example, the clutter level in a one-meter range cell cannot be very reliably predicted using a range-gating system with a minimum range-cell width of 10 meters.

The absence of reliable clutter information has resulted in development of the LFD being a two-stage, cyclic process. Because the LFD must be portable, its size and complexity must be minimized. Thus, to insure unneeded features are not designed into the LFD, one stage of the development process is essentially a learning stage that serves to define the problem (i.e., to estimate the clutter-suppression that is required). In the second development stage, instrumentation that is to permit the specified level of clutter-suppression to be achieved, is designed and implemented. The improved instrumentation is then tested to determine its adequacy for the LFD application and if necessary, is subsequently used to repeat the first stage of the development process (i.e., definition of the problem or equivalently, estimation of the clutter).

With each cycle of this development process, the ability to predict needed system improvements and to identify methods for achieving the needed improvements, becomes more precise. For example, at the inception of this program, the impact of clutter on the performance of the LFD was essentially unknown. By the end of the fourth year, the signal-noise graphs in Figures 17-19 had been developed. These simple graphs represent quantitative estimates of the level of receiver performance and clutter-suppression required to achieve reliable operation of the LFD and for the first time in this program, there is a reasonable idea of the performance goals that must be met.

By continuing the current development process, information such as the signal-noise graphs should become even more reliable. Ultimately, it should become possible to define the LFD's performance (false-alarm and detection probabilities) as a function of parameters such as range, range-cell size, observation period, clutter level, etc. Such knowledge will be essential if operation of the LFD is one day to be automated.

For the fifth year of this program, the cyclic development process will be continued. The present program goal is to reliably evaluate the performance limits of the existing LFD. This evaluation will include performing extensive

clutter measurements under a variety of field conditions. Results of the clutter measurements will be superimposed on appropriate signal-noise graphs (e.g., Figure 19) to estimate the level of clutter-suppression improvement needed to achieve reliable operation of the LFD.

To improve clutter-suppression, no major changes are planned in the basic FM-CW system currently being employed since careful evaluation of this approach (including that of a consulting engineer not affiliated with the program) revealed no inherent problems. Instead, efforts will focus on making the present range-gating system operate in a more-ideal manner. At this time, critical concerns are (1) eliminating system imperfections that prevent the range-gating system from working as effectively as expected based on the Fourier analysis results depicted in Figures 2 - 6 and (2) enhancing the capabilities of the receiver so the full ranging capabilities of the present FM-CW system can be employed.

It is suspected that system imperfections, such as nonlinearity in the tuning response of the 35 GHz Gunn oscillator and frequency-dependent variations in power during each frequency-sweep cycle, degrade suppression of clutter from sources outside the main range cell. In particular, range sidelobes, although suppressed, are still greater than predicted. As noted, range sidelobes are a problem because they permit clutter from sources outside the main-range cell to mask the desired target information. Of special concern is intrusion of clutter from close-in sources which can be especially strong since these return signals suffer little range-related attenuation.

Reflections from stationary objects such as the antenna (which would be eliminated if not for the range-sidelobe problem) or the ground may also be a problem. In general, it has been assumed that the observed clutter is due to returns from moving objects such as grass and trees. However, reflections from stationary objects may cause problems if phase-noise (frequency jitter), due to inherent variations in the 35 GHz Gunn oscillator or to noise in the modulating signal applied to the Gunn oscillator, are excessive. Any frequency instability during the sweep cycle will cause return signals detected from stationary objects to appear to be from moving objects. Since the return signals from the antenna or the ground can be quite large, it is conceivable that variations generated in this manner could be very significant. By measuring stationary return levels and the frequency instability of the Gunn oscillator, it should be possible to predict if any significant "clutter" is being generated by return

signals from stationary objects (these measurements are in progress). If so, a planned phaselock network will be completed and used to stabilize the frequency of the Gunn oscillator.

In addition to investigating the effects of system imperfections, a high priority task will be modification of the receiver so the full capabilities of the present range-gating system can be employed. The present system was designed to permit range-cell sizes as small as one-meter to be obtained. Because of receiver limitations, it has been possible to use the one-meter range cell only for ranges less than 25 meters. For longer ranges, wider range-cell sizes were necessary. Thus, the clutter-suppression possible with one-meter range cells is yet not known.

From the field test discussion, it can be recalled that range-cell widths of 3.7, 5.5, and 7.3 meters were employed in tests performed from 61, 91, and 122 meters, respectively. By making the range-cell width as small as one meter, significant improvements in performance appear practical. Again, the level of expected improvement is not known exactly. In general, reductions in range-cell size have improved clutter-suppression by a factor slightly better than that predicted from simple geometric considerations. Thus, there is reason to believe that the one-meter range cells will have a significant impact, particularly after the effects of other system imperfections have been eliminated or reduced.

It is possible that the clutter-suppression provided by the one-meter range cells will be inadequate for some applications. In view of this possibility, controlled measurements will be made for several different range-cell widths (e.g., 1, 2, 4, and 8 meters) to study the manner in which clutter varies as a function of range-cell width. Results of these measurements will then be used to predict if additional clutter-suppression can be achieved using smaller but practical range-cell widths. It appears that range-cell widths as small as a half meter could be achieved with appropriate modifications to the present range-gating system. For a maximum detection range of 100 meters, a half-meter range-cell corresponds to 200 individual range cells (i.e., maximum range / range-cell size = number of range cells). The practicality of evaluating this number of range cells will be determined by the willingness of the sponsor to invest in development of a suitable receiver.

In summary, efforts during the fourth year continued the consistent progress that has been made during this program. Efforts during the fifth year

will focus on refining the capabilities of the present FM-CW system. Several ideas are being considered that constitute major redesign of the LFD (e.g., a technique for achieving a wider band frequency sweep so that smaller range cells are possible, a fully digital receiver to simplify extraction of information from individual range cells, alternative antenna beam-shapes such as a fan-beam that might be more appropriate for interrogation of ground targets). However, there appears to be some risk involved in making major design changes before the imperfections in the present system can be eliminated or at least identified since any imperfections plaguing the present system could propagate through to the new design. The performance of the refined LFD is expected to be measurably better than that of the system used in the field tests in March and April (1986), especially when combined with the new signal processing system that is being implemented. It is not certain that the performance of the refined system will be adequate to fully satisfy all program ambitions. However, it should provide an accurate measure of the needed performance improvements as well as serve as an excellent base for development of the next-generation LFD.

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